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Leading the way with strain wave gear technology

2023 is shaping up to be iOptron's most innovative yet! Earlier we stepped on to the strain wave gear stage by introducing the highly anticipated HEM27 and HEM27EC. These two models provided a window into the freedom found through a drive system that didn't rely on a balanced payload to function. With no cumbersome counterweights or shafts, these mounts ushered in a new level of portability. This year iOptron will be expanding our strain wave gear products into 3 groups of SWG mounts, with a industry-leading total of 16 models!

HEM Hybrid Strain Wave Gear Mounts

The HEM group of iOptron SWG mounts consists of 5 models spread over 3 payload capacities. Each features a SWG with electronic friction break on the RA axis and lightweight, backlash-free worm gear on the Dec. The black anodized all-metal CNC-machined body serves as a rugged foundation to support the HEM mount's precise tracking and GoTo function. Models below include iPolar (unless noted). **EC** versions have precision encoders.

Model	Mount Weight	Maximum Payload	M.A.P.
HEM15 w/o iPolar	5.5lbs	15.4lbs	\$1,798.00
HEM15	5.5lbs	15.4lbs	\$1,898.00
HEM27 w/o iPolar	8.15lbs	29.7lbs	\$1,898.00
HEM27	8.15lbs	29.7lbs	\$1,998.00
HEM27 EC	8.15lbs	29.7lbs	\$3,298.00
HEM44 w/o iPolar	13.65lbs	44lbs	\$2,698.00
HEM44	13.65lbs	44lbs	\$2,798.00
HEM44 EC	13.65lbs	44lbs	\$4,148.00



HAE Dual AZ/EQ Strain Wave Gear Mounts

Dual SWG (RA and Dec axis) arrangement of the HAE group gives the user freedom to choose from an equatorial mode for imaging or Alt-Az for visual observing sessions. Utilizing SWG technology on both the RA and Dec axes completely alleviates the need to balance the system before use. Models below include iPolar (unless noted). Available as standard or EC (precision encoder) versions.

Model	Mount Weight	Maximum Payload	M.A.P.
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HAE29	8.15lbs	29.7lbs	\$2,098.00
HAE29 EC	8.15lbs	29.7lbs	\$3,348.00
HAE43 w/o iPolar	12.78lbs	44lbs	\$2,798.00
HAE43	12.78lbs	44lbs	\$2,898.00
HAE43 EC	12.78lbs	44lbs	\$4,248.00

HAZ Alt-Az Strain Wave Gear Mounts

HAZ iOptron's Alt-Az strain wave gear mount group sets the mark for portability and easy set-up. HAZ mounts support a variety of instruments allowing flexibility when needed, such as outreach programs, solar observation and satellite tracking. The multi-position saddle can be placed on top or to the side, perfect for accommodating binoculars. So easy to operate, just turn the mount on and it calibrates itself and slews to the first target utilizing our time-tested "Level and Go" technology.

Model	Mount Weight	Maximum Payload	M.A.P.
HAZ31	8.15lbs	31lbs	\$2,098.00
HAZ46	12.3lbs	47lbs	\$3,348.00

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Spiral galaxies are ubiquitous in the nearby universe, yet we still don't know how their patterns arise.

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ON THE COVER



New Zealand's North Island, as seen from the ISS in 2022

PHOTO: NASA JSC / NASA EARTH OBSERVATORY

ONLINE

TIPS FOR BEGINNERS

New to astronomy? Here's everything you need to jump into the fun. skyandtelescope.org/letsogo

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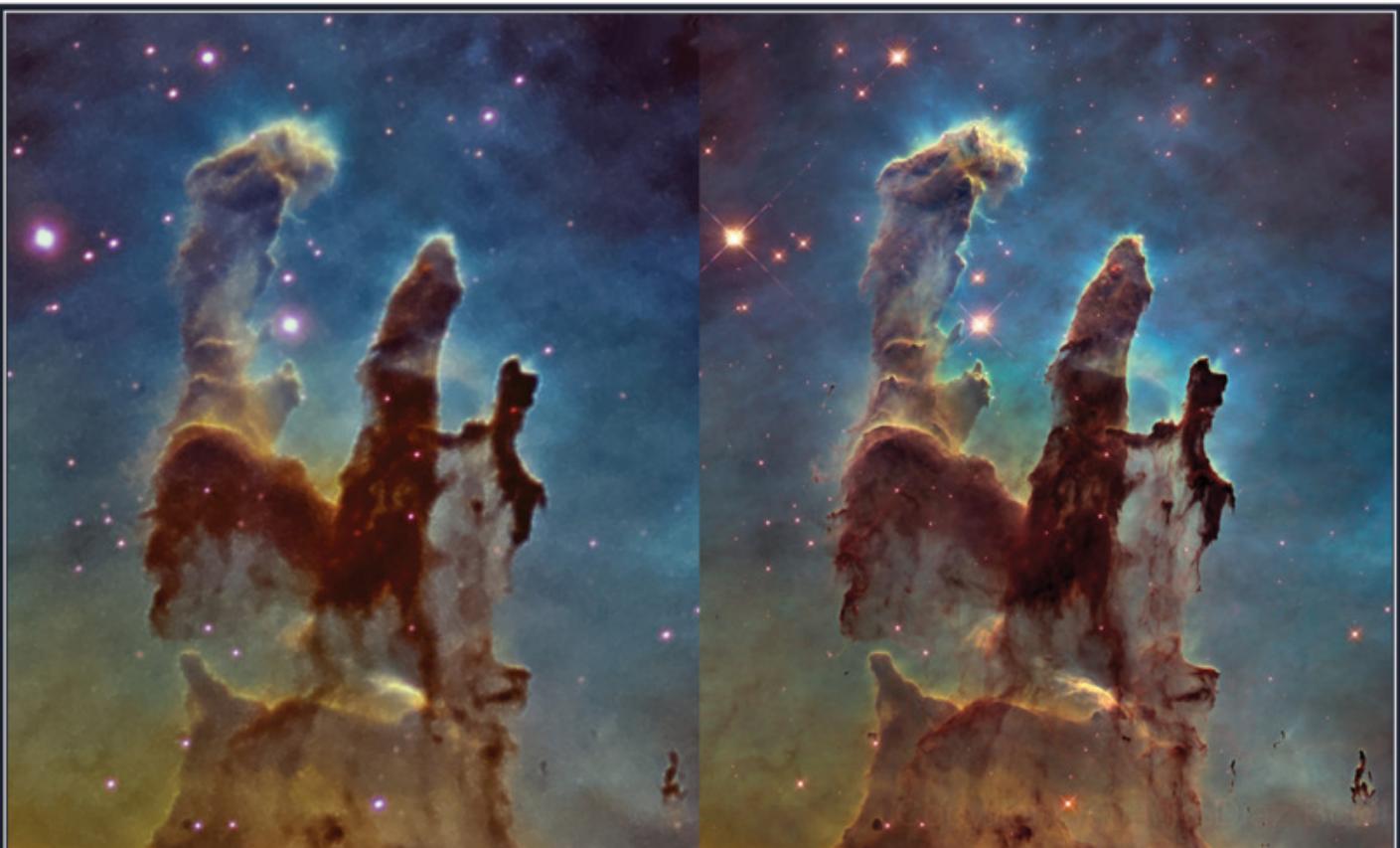
Find out what the sky looks like for your time and place. You can also print the chart as a handout. skyandtelescope.org/interactive-sky-chart

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The image on the right is the famous Pillars of Creation (M16) taken with the Wide Field Planetary Camera of the Hubble Space Telescope. The image on the left is taken with a QHY600M-PH Camera through a 7-inch refractor from the author's backyard in Buenos Aires. Courtesy Ignacio Diaz Bobillo. To see the original composition, resolution and acquisition details, visit the author's Astrobin gallery at https://www.astrobin.com/users/ignacio_db/

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SPECTRAL FLATNESS: "The bottom line is the spectral variation in the QHY600M's CMOS sensor is only 0.5%. So-called scientific back-illuminated CCD sensors are not nearly this good." *Alan Holmes, PhD, Testing the Spectral Flatness of the QHY600.*

PHOTOMETRY: "I did all of the tests, and was happy with the results." *Arne Henden, former Director of the AAVSO*

LINEARITY: "Very little noise, very good linearity, stable electronics and the possibility of using different operating modes make the QHY268 Mono [APS-C version -ed] an ideal camera for the advanced amateur that wants to give a contribution to science rather than just taking pretty images of the night sky." *Gianluca Rossi, Alto Observatory*



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Down to Earth



OUR FOCUS at *Sky & Telescope* is typically well beyond our own planet. In part that's because Earth is the only body in the solar system, indeed in the universe, that we humans can't observe as a whole (unless we're astronauts). So we commonly cast our gaze on objects much farther away — on other worlds circling the Sun right out to galaxies and other celestial treasures light-years away.

But now and then we aim closer to home. In this issue, you'll find more photos than usual of our beautiful world. Next to all the night-sky images, it can be refreshing — see, for example, the satellite shot on pages 34-35.

That striking photo opens our cover story this month, which asks a question scientists have pondered for decades: Where did Earth get its water? While our planet, as writer Javier Barbuzano notes, is 99.8% rock, we've got oceans and oceans of H₂O. And surface water is just part of it; lots more is likely locked up in minerals deep underground. Where did all that water originate? Barbuzano runs through the leading possibilities.



▲ A European Space Agency Meteosat satellite captured this image on March 23, 2022.

Tom Dobbins and Bill Sheehan's feature on page 22 concerns sunlight reflected off the Moon, but the article has everything to do with our planet. Earthshine — sunlight reflected from Earth to the Moon and then back again — is more than just an observer's treat. As the authors explain, it can actually help us study our planet. A key element contributing to alterations in our climate is how much sunlight Earth reflects back to space. Earthshine can help scientists monitor these fluctuations in our globe's albedo, or reflectivity.

That ghostly glow from the Moon might also aid us in our search for signs of life on exoplanets. Flora on our land and phytoplankton in our seas both have distinctive spectral signatures that, amazingly enough, scientists have detected in earthshine. If they can spot such signals in twice-reflected sunlight, why not in once-reflected starlight from distant worlds? That's the hope, anyway.

Other pieces in this issue also exhibit an earthbound bent. In Celestial Calendar starting on page 48, Bob King offers tips on how to spy Venus and Jupiter in the daytime. As he writes, "Seeing other worlds in a blue sky makes them seem closer somehow — like they're part of an earthly scene." We wrap up on page 84 with a look at phenomena in our own atmosphere: an update from backyard astronomer Jay Brausch on his decades-long watch for aurorae high over his home in North Dakota.

We hope you enjoy this quasi-geocentric issue.

Editor in Chief

EUMETSAT / ESA

Editorial Correspondence

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An Edge-On Masterpiece

I just got done reading Howard Banich's article "The Great Edge-On Galaxy of Autumn" (S&T: Nov. 2022, p. 28), which was very interesting. It reminded me that I had imaged NGC 891 from Chiefland, Florida, back in the fall of 2018. It made me interested to review what my image had looked like. I was able to detect the two smaller galaxies on either side of NGC 891 that Banich mentions in his article. Again, great article! Thanks!

Sandy Goodstein
Lebanon, Pennsylvania

◀ Sandy Goodstein captured this image of NGC 891 through a Celestron 11-inch EdgeHD Schmidt-Cassegrain with an SBIG ST-4000XCM camera.

A Fine Southern Beacon

I enjoyed Fred Schaaf's *Evenings with the Stars* column about Fomalhaut (S&T: Oct. 2022, p. 45) and felt compelled to add a couple of additional observations related to my favorite bright star. From my latitude of 42.5°N and thereabouts, as Fomalhaut (and Altair) set, Sirius rises. This celestial concurrence presents a brief window between August and January during which most people in the continental United States may observe 11 first-magnitude stars at once.

Fomalhaut also helps point the way to the horizon-skimming Alnair (Alpha Gruis) and Beta Gruis. The latter, a variable, 2nd-magnitude, red M-class star, lies to the right of the fish's mouth, Fomalhaut. The somewhat brighter B-class Alnair is a study in contrast that culminates a bit earlier, soon after Enif (Epsilon Pegasi), the nose of Pegasus, crosses the meridian. Both stars in the Crane are roughly -46.5° declination, so binoculars are required from the Illinois-Wisconsin border where I live, though an eagle-eyed observer with a dark, clear horizon may be able to make out Alnair or even Beta Gruis on a perfectly clear, post-cold front evening from as far north as Springfield, Illinois.

I hope Schaaf continues writing articles that emphasize learning the sky with one's eyes.

Ed Furlong
Walworth, Wisconsin

Speak the Plain Truth . . .

In "Cut Out the Undercuts" (S&T: Nov. 2022, p. 70), Jerry Oltion is dead on-target regarding eyepiece barrel undercuts and "backward" finder mount saddles. Every time I see either, I wonder how long we must wait. Both are aggravating at the least, often worse.

Never say never (again), but in 35 years of observing I've only had an eyepiece fall out once. And that was because I simply didn't tighten the set screw. The ironic part? The eyepiece had an undercut barrel! It's too bad manufacturers don't offer optional smooth barrels.

Len Philpot
Pineville, Louisiana

In Tycho Brahe's Footsteps

I enjoyed Jerry Oltion's "Replicating the Great Quadrant" (S&T: June 2021, p. 72), about building a replica of Tycho Brahe's impressive instrument. A few years ago, I became interested in finding out exactly how Tycho constructed his

star catalog, so I undertook a project to recreate his database of angular measurements. I wanted to construct my own catalog using his algorithms and techniques. This required building a four-axis telescope, with arcminute absolute pointing, to serve as Tycho's "trigonal sextant." I spent about 18 months making observations.

After reducing the thousands of data points to form the catalog, I was able to recreate Tycho's catalog to good accuracy, as well as extract other astronomical parameters like length of the year and the diameter of the Sun.

For those interested in such a project, and the telescope required, please visit <https://is.gd/BraheRecreation>.

Dave Skillman
Greenbelt, Maryland

Going the Distance

Govert Schilling's article "Keep Your Distance" (S&T: Oct. 2022, p. 12) nicely covers the history of astronomical distance measurements, which started with terrestrial measurements. The circumference of Earth would have been necessary for determining the baseline during the triangulation to Mars, from which the astronomical unit was derived.

In 200 BCE, Eratosthenes measured Earth's circumference by noting that on the longest day of the year, the Sun was at an angle of about 7° in Alexandria, while in Aswan in southern Egypt it was directly overhead. Someone likely paced the distance from the north to the south end of Egypt to complete the triangle. But from these measurements, he was able to determine the circumference to within a reasonable approximation of modern measurements. One could say that Edwin Hubble's measurement of the distance to Andromeda could be traced back to an Egyptian 2,200 years ago pacing the length of Egypt.

Kenneth A. Devine
Aurora, Ontario

I enjoyed the article by Govert Schilling. I was very fortunate to have a gifted astronomy teacher and friend, William Gutsch, an accomplished educational expert in astronomy and past chairman

of the Hayden Planetarium. Gutsch has a way of making astronomy exciting, and in our class he dealt with ways we measure or estimate distances in space. One key, as I recall, was the overlap of measurement "sticks" to ensure accuracy.

While I am still trying to comprehend the final page in Schilling's article, until recently (I am now 70) I had not realized that space itself is expanding. This was not evident to me in George Abell's *Exploration of the Universe* introductory text or other sources, even though I have a minor in physics, until I recently read the intro text of *The Cosmos: Astronomy in the New Millennium* by [the late] Jay M. Pasachoff and Alex Filippenko. I had always assumed redshift was totally due to recessional velocities.

John M. Roberts
Richmond, Virginia

As a long-time subscriber, I very much appreciate the outstanding articles in the monthly editions of *S&T*. "Keep

Your Distance" is no exception. I found it to be very interesting and informative on how we determine cosmic distances. My only comment is that the article made no mention of space dust and its effect on the apparent brightness of stars and galaxies when determining distances from us.

I believe the cumulative effect of space dust on apparent brightness can lead to substantial distance errors, especially with objects millions or billions of light-years away. Can space dust's effect on apparent brightness affect the determination of cosmic distances, or is it considered negligible?

Angelo DiDonato
Macomb, Michigan

 **Camille Carlisle replies:** You pose a very good question. Dust in a galaxy can and does affect the light curve of

a supernova or Cepheid observed within that galaxy. Astronomers correct for dust's reddening effect when measuring cosmic distances. But there is debate about just how accurate these corrections are. For example, some have suggested that dust calibration is throwing off the Cepheid-based measurements of the universe's current expansion rate and causing the tension between different results (*S&T*: Mar. 2022, p. 14). Other methods, such as using "tip of the red-giant branch" stars, might avoid this problem, because those stars tend to be in less dusty environs.

An exceptionally dusty galaxy can also look so red that it appears to be a galaxy at a much larger distance (<https://is.gd/WebbDistance>). We can solve this ambiguity with careful spectral measurements.

This is one of the reasons why it's so important to have multiple ways of measuring distances.

75, 50 & 25 YEARS AGO

by Roger W. Sinnott

1948



● March 1948

Gigantic Crater "In South Africa there is an unusual topographical feature whose origin seems to have defied explanation on the basis of orthodox geological dynamics. Roughly circular and about 30 miles in diameter, the formation is known as the Vredefort ring structure . . .

"Of five geological theories, two have supposed magmatic upthrust to be the primary cause of the ring formation; a third, tangential force of the kind ordinarily applicable to mountain building . . . Proof of the meteoric theory . . . seems almost impossible since the erosion of over 200 million years has destroyed the original relief and may have removed all meteoric remnants."

Updates from a 2022 study: Two billion years ago, the impact of a 15-mi-wide (25-km-wide) asteroid created Vredefort. The crater was originally 155 mi (250 km) across.

1973



1998



● March 1973

Orange Soil "One of the many stories still unfolding [from Apollo 17] is that of the so-called orange soil discovered by geologist-astronaut Harrison H. Schmitt . . . As soon as the orange material got to Houston, it was given special attention at the Lunar Receiving Laboratory. . . .

"At a press conference, William Phinney, chief of the geology branch at the Manned Spacecraft Center, described its appearance under a binocular microscope: . . . 'The material is essentially the finest-grained soil we have yet seen from the moon, with a grain size of 40 microns instead of the usual 70-80 microns. More than 90 percent of this soil is glass, [and much] of the glass is orange, especially the finer grains. There are a few percent of mineral grains, most of them partly coated with the same glass.'"

Decades later, analysis of this volcanic glass brought another surprise: The Moon's interior magma holds as much water as Earth's.

● March 1998

Thanks, Moon "Throughout the millenniums the Moon has inspired and influenced art, romance, and endeavor. Now it is becoming apparent that life itself owes a lot to our satellite. After Earth's surface cooled and oceans formed, . . . the Moon kept the Earth's rotational axis relatively stable. Studies have shown that without the Moon, the tilt of Earth's axis would vary chaotically between 0° and 85°. . . .

"Darren M. Williams and James F. Kasting (Pennsylvania State University) modeled Earth's climate to examine how habitable our planet would be. [They report] that if Earth's axis tipped completely over so that the Earth spins 'on its side' (much as Uranus does), the zone we now call the tropics could have permanent snow cover. The poles, for their part, would endure extreme temperature swings . . ."

Recent work confirms a stabilizing effect of the Moon but finds that the tilt of a moonless Earth would not vary quite so chaotically.



SPACE

Liftoff! NASA Launches Artemis 1 Mission to the Moon

AFTER A LONG WAIT, NASA's new super-heavy lift Space Launch System (SLS) Block 1 rocket headed for the Moon in the wee hours of November 16th. The launch took place from the Kennedy Space Center in Florida.

The successful night launch came after four wet dress rehearsals, none of which made it down to the T-10 second mark. Multiple issues also plagued the launch itself, delaying it from an initial date of August 29th.

Although NASA is footing the bulk of the launch's \$4 billion bill, the Arte-

mis program is an international effort with contributions from the European Space Agency, the Japan Aerospace Exploration Agency, Israel, and the Italian Space Agency.

The SLS uses two Space Shuttle-era solid rocket boosters and a core stage containing four liquid-propellant engines. The boosters and engines have flown on previous Shuttle missions. The Block 1 rocket weighs more than 2,500 metric tons, lighter than Apollo's Saturn V, and it can send 27 tons to deep space.

The main objective of Artemis 1 is to test the integrity of the Orion capsule, which will carry future crew. The mission will also study the radiation exposure those human passengers will receive. To this end, three manne-

SOLAR SYSTEM

Two Fresh Impacts Probe Martian Crust

METEOROID STRIKES have created two of the largest seismic events on Mars, as recorded to date by NASA's Insight lander. The impacts provided a peek inside the Red Planet, scientists report in the October 28th *Science*.

On December 24, 2021, Insight detected a 4th-magnitude marsquake. A team led by Liliya Posiolova (Malin Space Science Systems) later picked up a fresh crater in images from the Mars

Reconnaissance Orbiter images. Using daily surface maps from the probe's Mars Color Imager, the team placed the crater's formation in the same 24-hour window in which InSight detected the marsquake. The crater's location — estimated to be 3,460 kilometers (2,150 miles) from InSight in the Amazonis Planitia region — also matches the marsquake's estimated epicenter.

The find triggered a search for other impacts that would have made large

► Boulder-size blocks of water ice can be seen around the rim of a Martian impact crater created on December 24, 2021.

quins went along for the ride, recording conditions during launch, deep space, and reentry.

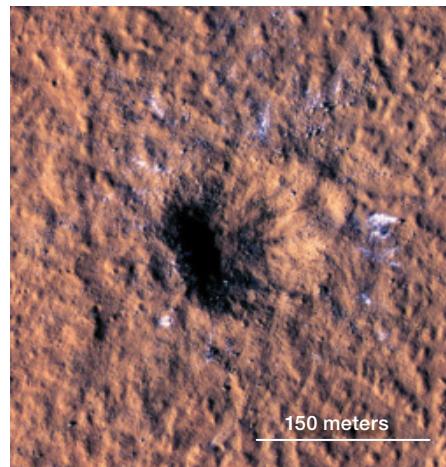
The Orion spacecraft's stage adapter ring carried 10 CubeSats bound for the Moon and beyond. One of these, Japan's Omotenashi, even aimed to land *on* the Moon; however, communications were unstable, and commands to initiate a landing sequence did not go through. (Three other CubeSats initially intended for Artemis missed the integration window and will have to find alternative paths to the Moon.) Read details on the CubeSats here: <https://is.gd/Artemis1>.

Orion is solar-powered and cannot be in the shadow of Earth or the Moon for more than 90 minutes. This was one of several factors that dictated the launch windows, flight-path geometry, and duration of the mission.

The 25.5-day mission sent Orion past the Moon and back, including two close lunar flybys. The closest approach to the Moon took the capsule just 130 km (81 miles) above the lunar surface on day five. It then reached a maximum distance of 432,196 km from Earth, the farthest a habitable vehicle has gone (and returned from). As of press time, a second lunar flyby is expected December 5th and return to Earth on the 11th.

Artemis 2, tentatively set for launch in May 2024, will carry crew for a lunar flyby and return. The first crewed landing of the Artemis project will occur no earlier than 2025 with Artemis 3.

■ DAVID DICKINSON



ARTEMS: KIRBY KAHLER; MARS IMPACT: NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA

Is This the Lightest Neutron Star?

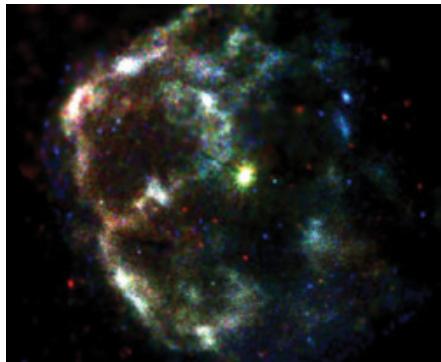
A TEAM OF ASTRONOMERS claims to have measured the lightest neutron star, a finding that could entail new physics. But others say the evidence doesn't yet back such an extraordinary claim.

The object in question is a well-known neutron star at the heart of the supernova remnant HESS J1731-347, more than 8,000 light-years away in Scorpius. After reanalyzing X-ray observations taken over six years with the XMM-Newton and Suzaku space observatories, Victor Doroshenko (University of Tübingen, Germany) and colleagues concluded October 24th in *Nature Astronomy* that this neutron star has only 80% of the Sun's mass.

Neutron stars are not supposed to be this light. "A 0.8-solar-mass neutron star is probably something which can cause discomfort for most people in the field," Doroshenko acknowledges.

To estimate the neutron star's mass, the team fit the X-ray spectra with a model of the heat emitted from its atmosphere, which they assumed is carbon-rich and radiating uniformly.

The results point to a lightweight neutron star, with between 0.7 and 1 solar mass, and a girth of some 10.4 kilometers (6.5 miles). If it is a neutron star, its mass and radius indicate a strange interior, one in which neutrons dissolve into their constituent



▲ This X-ray image depicts the supernova remnant HESS J1731-347. The bright source at center is a hot neutron star.

quarks before transforming into even more exotic particles.

Previous observations have indicated no such breakdown inside neutron stars (*S&T*: Aug. 2021, p. 10), but all the measurements have enough wiggle room that there are no direct contradictions.

"This would be an amazing result if true," says Cole Miller (University of Maryland, College Park), who wasn't involved in the study. But he says the assumptions made aren't justified. For example, if only a small part of the neutron star's surface radiates, or its atmosphere were more hydrogen than carbon, then the best-fit model could have a larger mass.

"I do want to say that this type of work is certainly important," Miller adds. "It's just that more is needed to be dotted and t's crossed to arrive firmly at such an exciting conclusion."

■ MONICA YOUNG

quakes. Posiolova's team discovered another cluster of new craters, associated with an impact on September 18, 2021, that also created a 4.1-magnitude event. These craters lie 7,455 kilometers from Insight.

These two strong marsquakes generated *surface waves* that traveled through the Martian crust. Doyeon Kim (ETH Zürich) and colleagues used these waves to sample the crust not only directly under the lander, as had been done before, but also all along the great circles that connect the lander and the distant points of impact. The

measurements suggest that, for reasons yet unknown, the crust is more porous under Elysium Planitia, where the lander sits, than elsewhere.

The crust along these tracks also appears to have a single layer of uniform density down to 30 km, a find that runs counter to previous analyses that found a two- or three-layered crust beneath Insight (*S&T*: Nov. 2021, p. 8).

Tantalizingly, the impacts also excavated water ice at latitudes as low as 35°N — the closest to the equator that subsurface ice has been found on Mars.

■ DAVID DICKINSON

IN BRIEF

Satellite vs. Stars

The recently launched prototype of a satellite constellation, named BlueWalker 3 (*S&T*: Jan. 2023, p. 10), brightened significantly as it unfolded its giant flat-panel antenna array. *S&T* readers and others recorded the brightness of BlueWalker 3 before and after unfolding. Early results indicate that the satellite in its folded-up configuration was relatively faint, with magnitudes between 4 and 8, depending on the distance to the satellite as well as its illumination by the Sun. But on the morning of November 11th, Scott Harrington in Arkansas and Paul Maley in Arizona reported that the satellite had suddenly brightened to magnitude 1.5 and 1.0, respectively. Harrington and Maley made additional observations through November 14th; Richard Cole processed much of the data. Post-deployment magnitudes range from 4 to 0. The panel's deployment thus resulted in about a 4-magnitude change, becoming 40 times brighter in the sky. The AST SpaceMobile company plans to orbit at least 100 more satellites modeled after BlueWalker 3 — but with even larger panels — by the end of 2024.

■ ANTHONY MALLAMA

Arecibo Legacy Catalog

Astronomers have released near-Earth asteroid radar observations obtained between December 2017 and December 2019 using the Arecibo Observatory's 305-meter radio dish. The cache of radar observations, published in the September 2022 *Planetary Science Journal*, includes 191 near-Earth asteroids. The Arecibo group's main goal is to support NASA's planetary defense activities by characterizing asteroids. The radar data will help astronomers work out an asteroid's distance, speed, shape, and rotation period. Among other things, the catalog includes 3D radar images of 37 asteroids. "It is a difficult and time-consuming process to extract this information from radar data, and they are usually published one at a time," says Stephen Lowry (University of Kent, UK), who wasn't involved in the study. According to team lead Anne Virkki (University of Helsinki), this data release is just the start. "This paper is like a teaser for a full movie," she says. "In fact, there's still a lot of high-quality data to be analyzed in detail, which could even support planning future spacecraft missions to small bodies."

■ COLIN STUART



This artist's illustration shows a white dwarf star accreting planetary debris.

STARS

Ancient White Dwarf Hosts Planetary Graveyard

THE DEATH THROES of other suns can quite literally be the end of the world for their planets, as they are vaporized or placed on infalling orbits. Now, scientists report in the December *Monthly Notices of the Royal Astronomical Society* an analysis of one of the oldest of these planetary graveyards: a red-hued white dwarf about 91 light-years away that's polluted with planetary debris.

The European Space Agency's Gaia spacecraft first identified this white dwarf, WDJ2147-4035, as having unusual properties. Abigail Elms (University of Warwick, UK) analyzed this and another unusual one, WDJ1922+0233, which is bluer and a bit farther away at 128 light-years. Both stellar remnants were already known to be contaminated and cool.

To take a closer look at both of the white dwarfs' composition and temperature, Elms and colleagues analyzed spectra from the Very Large Telescope as well as brightness measurements from the Dark Energy Camera at the Cerro Tololo Inter-American Observatory, both in Chile.

"WDJ2147-4035 is the reddest and faintest [polluted] white dwarf discovered in our galaxy," says Elms. It's also

the coolest polluted white dwarf yet identified. While white dwarfs start out blazing hot, they can only cool over time, and Elms' team estimates that the reddish white dwarf has been cooling for more than 10 billion years. The bluer white dwarf is the second-coolest polluted white dwarf known, and Elms' team estimates it's 9 billion years old.

There are only a handful of polluted white dwarfs anywhere near as cool, says Siyi Xu (Gemini Observatory), who wasn't involved in the study. But she adds that uncertainties involved in calculating the age from a white dwarf's temperature mean that it's hard to say with certainty whether the objects Elms' team described are for sure the oldest known.

Observing white dwarfs consuming their ancient planetary systems provides a rare chance to see what the small bodies were made of. Elms' team found that, while the debris falling onto the bluer star has a composition similar to that of the Earth's continental crust, the redder one's rubble has a makeup that's harder to explain, with unusually high amounts of potassium and lithium.

■ **ELISE CUTTS**

GALAXIES

M77: A Galactic Particle Accelerator

ASTRONOMERS HAVE TRACED dozens of neutrinos back to the nearby galaxy NGC 1068 (M77), only the second individual source known to produce copious amounts of the uncharged, almost massless particle.

Traveling at near-light speed, neutrinos pass through almost everything in their way, only rarely interacting with other particles. It takes a collection of more than 5,000 light-sensitive detectors buried in one cubic kilometer of Antarctic ice — the IceCube Neutrino Observatory — to register the tiny flashes that mark speeding *muons* (heavy electrons), produced in turn by neutrino interactions.

As reported in the November 4th *Science*, the IceCube Collaboration collected 79 high-energy neutrinos between 2011 and 2020 from the direction of M77. The high-energy neutrinos were likely a byproduct of particle collisions near the supermassive black hole that sits in the galaxy's core.

Four years ago, IceCube identified the first known source of cosmic neutrinos: TXS 0506+056 (S&T: Nov. 2018, p. 11). This active galaxy is known as a *blazar* because its central black hole is pointing one of its plasma jets toward Earth. More recently, scientists have reported a more general link between the distribution of distant blazars on the sky and the arrival directions of high-energy neutrinos (<https://is.gd/blazars>).

But the new discovery suggests that blazars aren't the only neutrino factories out there. Indeed, we need more than blazars to explain all the high-energy neutrinos IceCube detects, writes Kohta Murase (Penn State) in an accompanying commentary in *Science*.

Future observations, in particular from Europe's Cubic Kilometre Neutrino Telescope (KM3NeT) that's under construction on the bottom of the Mediterranean Sea, will probably clinch the case; it will have a much better directional sensitivity than IceCube.

■ **GOVERT SCHILLING**

SOLAR SYSTEM

Was 'Oumuamua a Chunk of an Exo-Pluto?

THE INTERSTELLAR OBJECT 'Oumuamua (1I/2017 U1) was an odd duck (S&T: Oct. 2018, p. 20). Its strong brightness variations suggested a pancake-like aspect ratio of 6:6:1. It also slowed more than expected — 10 times more than it would if it were a typical comet — as it exited the solar system. Yet it exhibited no visible coma, nor a tail of either dust or gas.

At the Exoplanets in Our Backyard 2 workshop held in November in Albuquerque, New Mexico, Steve Desch (Arizona State University) presented a plausible scenario that accounts for all of these aspects.

Desch and team member Alan Jackson (also Arizona State) investigated the sublimation behavior of various ices common in the outer solar system. They found that nitrogen ice could provide the right reflectivity, size, and mass to reproduce 'Oumuamua's cometary trajectory *without* producing any of the hallmarks of comets.



▲ Studies have shown 'Oumuamua to have a pancake-like 6:6:1 aspect ratio.

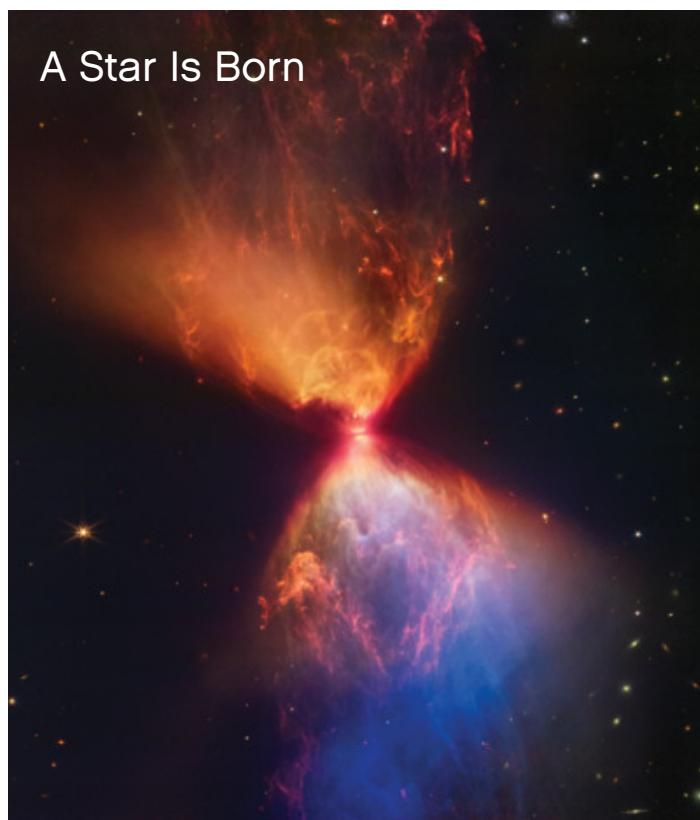
Pure nitrogen-ice would solve other puzzles, too, such as how the body survived passage within 0.26 astronomical unit (a.u.) of the Sun. According to Desch and Jackson's model, 'Oumuamua would have lost 95% — most but not all — of its mass by the time it exited the inner solar system (when it was discovered). Such extreme mass loss would also explain its shape: If you add

20 times the present mass in concentric layers around the present pancake, reversing its evaporation by the Sun, the original body would have had a much more normal 2:1 aspect ratio.

Desch suggests that the chunk came from a Pluto-like object around a low-mass star (M8 or smaller). Such stars are more common than the Sun, and they also provide more favorable environments for nitrogen-ice-covered worlds. While the solar system might have ejected some 100 trillion ice fragments in its lifetime, that's not enough to explain the statistics of finding 'Oumuamua. However, more abundant M stars could each have ejected 40 times more fragments, making 'Oumuamua's discovery more likely.

'Oumuamua's appearance in our backyard is therefore a probable accident, Desch argues — and a recent one, too. Based on its trajectory, which lies in the galactic plane and has a relatively low speed for an interstellar interloper, 'Oumuamua exited its parent system up to a few hundred million years ago.

■ EMILY LAKDAWALLA



At visible wavelengths, the Taurus Molecular Cloud appears as a dark nebula of dust and gas. But longer wavelengths have pierced the veil to reveal a bustling stellar nursery. At some 450 light-years away, it's one of the nearest such regions, home to at least 250 infant stars. The James Webb Space Telescope has turned its infrared eyes on one of these, designated L1527. This protostar is a hot blob of gas that has only 20% to 40% the Sun's mass. At only about 100,000 years old, it hasn't yet begun fusion in its core. It's still feeding on the cloud around it, which funnels gas and dust into a disk that's visible as a dark line across the middle of the image. That line is a few hundred astronomical units long, about the size of our solar system. As it feeds, this infant star also ejects mass, clearing out space above and below the disk. The star's light suffuses these emptied regions. Dust still veils our view, just some regions less than others: Blue areas have less dust in front of them, while light that must pass through more dust appears orange. This view represents a look back in time at a star very like our Sun just after it was born.

■ MONICA YOUNG

Read details at <https://is.gd/protostar>.

Nudging a Space Rock

That's one small change in an asteroid's orbit, one giant leap for humanity.



ON SEPTEMBER 26, 2022, the Double Asteroid Redirection Test (DART) spacecraft ended its existence in spectacular fashion by smashing into the asteroid Dimorphos (S&T: Jan. 2023, p. 8). Many of us watched spellbound as DART's cameras fixed upon the approaching target. At first, we saw only Dimorphos's larger orbital companion, 65803 Didymos, as a bright pixel, but soon it resolved into two objects. In the final minutes, the target suddenly loomed, filling the screen with a final, brief, fantastically detailed glimpse of its surface (see video at <https://is.gd/DARTsmash>).

The approach reminded me of my student days witnessing the Voyager encounters. The monitors at JPL would show a distant target growing gradually for days, followed by a few hours of quickening expansion to a differentiated object that filled the screen. I'd pretend the monitors were windows and we were flying past newly seen worlds.

I had that sensation again with the New Horizons spacecraft at Pluto in 2015, and now again with DART. Except that those other encounters were flybys, not crash-intos. And instead of days, this event took place within an hour. You could almost hear the swooping Star Trek alert sirens and the command to "Brace for impact!"

▲ The asteroid moonlet Dimorphos, roughly 160 meters (525 feet) long, appears 2.5 minutes, 11 seconds, and 2 seconds before the DART spacecraft intentionally crashed into it.

The impact shortened the roughly 12-hour orbit of Dimorphos around Didymos by about 32 minutes (S&T: Feb. 2023, p. 9). Such a small change might sound inconsequential. But arguably it represents a significant turning point in the history of our planet, our biosphere, and our solar system. The influence of the Anthropocene Epoch, marked by humans as a geological force, has begun to extend off-planet.

I don't know who first said that the difference between us and the dinosaurs is that they lacked a space program, but this joke is both funny and profound. Our solar system now has a new kind of planet — one that can begin to defend itself. The knowledge gained will help us forestall dangerous cosmic impacts that, if we waited long enough and did nothing, would inevitably cause regional destruction and, eventually, new mass extinctions on Earth. We're no longer helpless against this threat, and so, assuming we keep our act together and retain a technologically advancing global civilization, our biosphere and our planet need never again suffer such catastrophes.

Before we get too cocky, though, remember that dinosaurs walked the planet for 180 million years. Humans have been here for a few percent of that. And our burst of technical ingenuity has created new, self-imposed threats. Need I enumerate them? We certainly are gaining skills that could allow us to survive while the big lizards perished. But whether our wisdom keeps pace with our prowess and allows us to create the kind of global society that can harness that cleverness in the service of dinosaur-scale longevity is still TBD.

Back in the 1990s, Carl Sagan warned against messing with asteroids, lest someone get the crazy idea to direct one towards Earth. But in a world armed with thousands of nuclear weapons, that's the least of our worries. At least now we're taking baby steps toward protecting ourselves against a truly long-term, planetary-scale threat.

We, the adolescent technological species from Earth, have started, ever so slightly, to rearrange the solar system. Hopefully this is part of growing up. If so, then someday we may save not just our species but our biosphere.

■ Contributing Editor DAVID GRINSPOON is author of *Earth in Human Hands: Shaping Our Planet's Future*.

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Image courtesy HTA Dana Edmunds



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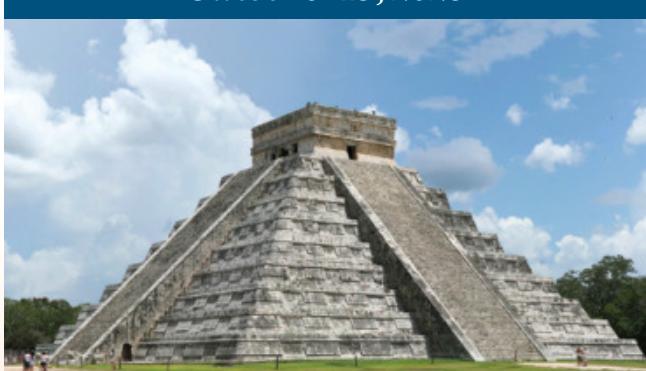


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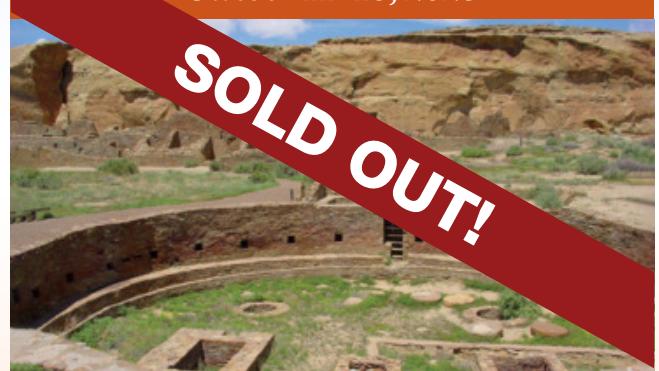


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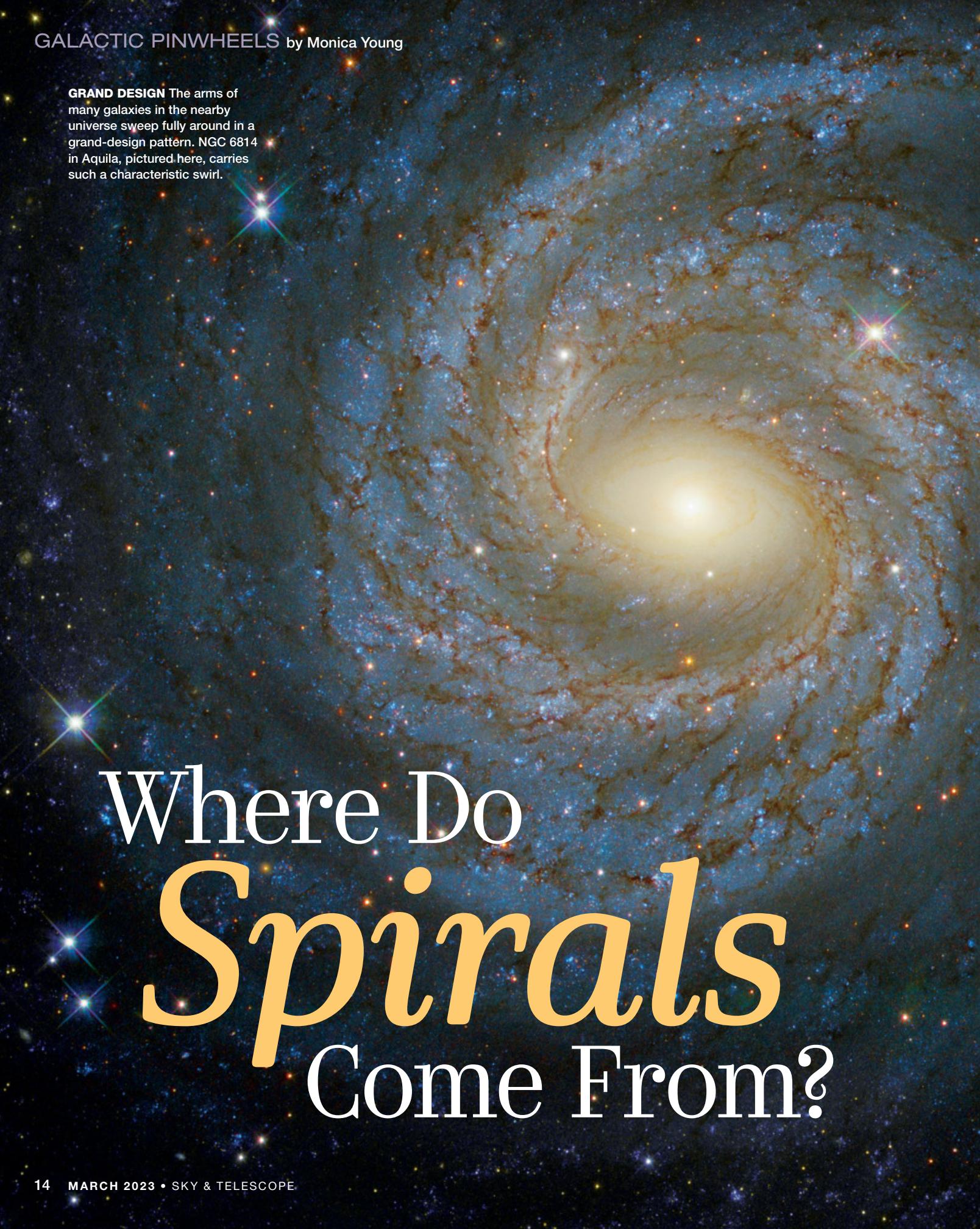


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GRAND DESIGN The arms of many galaxies in the nearby universe sweep fully around in a grand-design pattern. NGC 6814 in Aquila, pictured here, carries such a characteristic swirl.



Where Do *Spirals* Come From?



Spirals are ubiquitous among galaxies in the nearby universe, but we still don't know how these patterns arise.

Seen through a telescope, spiral galaxies are surprisingly subtle — faint and fuzzy things. Yet the structure they possess captures the viewer's imagination. Whether you glimpse the grand swirls of the Whirlpool (M51) or the frizzy petals of the Sunflower (M63), the patterns become all the more incredible when you realize they're shaped by the multitudinous tugs and nudges among billions of stars.

These simple individual interactions add up to far-reaching forces that have proven difficult to untangle. Astronomers observed galactic spirals even before they knew what galaxies were, but sound ideas explaining the pattern's origin have come only in recent decades.

Now, even though astronomers agree on the primary mechanism that propagates a spiral pattern, they still argue about what sets it all in motion. What is clear, though, is that spiral arms aren't just pretty. They play an essential role in shaping galaxies — including our own.

What Are Spiral Arms?

Spirals are easy to see even at great distances because bright regions of active starbirth trace the arms. But not every spiral looks the same. The most pleasing to view are those with two sweeping arms that wrap around the galaxy in a *grand-design* pattern. Others with multiple arms — whether three or four or just a fuzzy mess of swirls — are called *flocculent*.

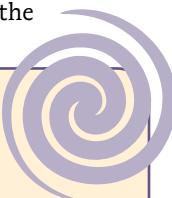
We see these spirals, in whatever form, across many wavelengths. Mid-infrared light spotlights *young stellar objects*, the about-to-be stars whose heat shines through the dust. Live-large-die-young O and B stars emit blue and ultraviolet light from their place along the spirals' spines. Radio waves emitted from warm gas near these young stars, as well as from cool hydrogen gas across the galaxy, also reveal a spiral shape.

The pattern isn't found only in gas and stars. Dust follows the spiral, too, though dust arms are often offset from those traced by stars. Even a galaxy's loose electrons and magnetic fields align with its arms.

Any small disturbance can create a galactic swirl: *Differential rotation*, in which the inner parts rotate more quickly than the outer parts, sees to that. You can see similar shapes in your morning coffee when you stir in the

Spiral Surfing

The Milky Way's spiral arms rotate at 210 kilometers per second (470,000 mph), while the Sun speeds along at 240 km/s through the galaxy. So our solar system surfs in and out of our galaxy's arms over time.



cream. But a spiral made of cream — or stars, for that matter — doesn't last long. As the galaxy rotates, such spirals wind up, tightening over time and eventually disappearing.

Instead, astronomers have come to realize that galactic spiral arms are something different: They are the signature of *density waves*, surges of compression that slosh through the disk's gas, dust, and stars. The density in spiral arms can be some 10% to 20% higher than in their surroundings, a small difference that's nevertheless enough to ignite the formation of new stars.

But those new stars don't stay with the arm. Elena D'Onghia (University of Wisconsin, Madison) likens a star in a spiral galaxy to a swimmer floating in the ocean. Even though a swimmer moves up and down as a wave passes by, afterwards they're close to where they were before. Stars, like swimmers, don't constitute the waves; they just ride the surf.

Spirals are so common — making up 70% of galaxies in the nearby universe — that many initially thought the patterns must endure over many billions of years. So when Chia-Ch'iao Lin and Frank Shu (both then at MIT) first put forward the idea of density waves in the mid-1960s, they proposed it as a regularly shaped and long-lived phenomenon. Spiral arms under the Lin-Shu hypothesis appear stationary, like a pure tone resonating long after a bell was rung. The only change with time is their overall rotation.

But mounting evidence suggests density waves don't last as long as once thought. Some of the evidence has come in the form of computer simulations. Theorists construct these simulations using a large number of star-size bodies and factoring in the gas that surrounds them, then they set up a wave and watch what happens. "People have tried very hard with *N*-body simulations to make systems [long-lasting], and they just don't seem to be able to do it," says Scott Tremaine (Institute for Advanced Study), who literally wrote the textbook on galactic astronomy. "Galaxies aren't very good bells."

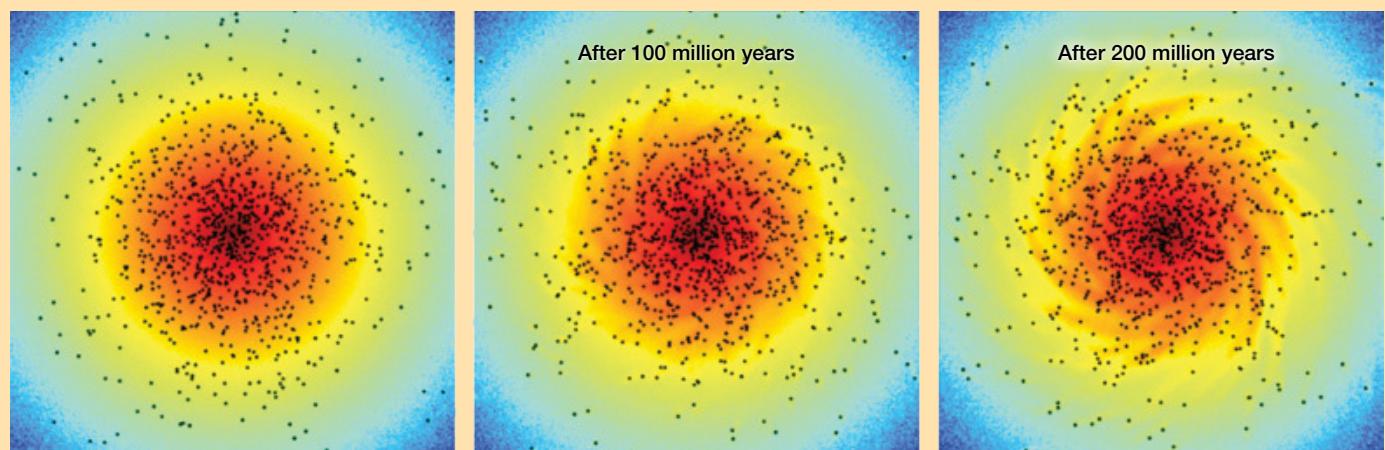


▲ **FLOCULENT** Some galaxies, such as the Sunflower Galaxy (M63), captured here by the Hubble Space Telescope, may have multiple arms or just a fizzy mess of swirls.

Theorist Jerry Sellwood (University of Arizona) agrees. "The idea that spirals are long-lived and slowly evolving has basically been debunked," he says. "Simulations for years have shown that spirals keep coming and going."

The formation of a spiral arm may even remove the conditions that enabled it to form in the first place. The sloshing of a density wave adds randomness to stellar motions, wobbling their orbits around the galactic center and dampening their gravitational interactions. Once that happens, Tremaine says, "the galaxy can't support the wave as well anymore, and the wave tends to go away."

Grand-design arms are probably the best examples of density waves in action. "Some of the grand-design spirals are almost certainly like a bell that's just been hit," Tremaine



▲ **SWINGING 'ROUND** Simulation frames show a galaxy with 100 million stars (highest density colored red, lowest density blue). Amid the stars are 1,000 randomly placed clumps (black dots), each with the mass of a typical star-forming cloud. The clumps' gravity disturbs the surrounding material via a process called *swing amplification*, naturally producing multiple spiral arms.

says. But even then, the sweeping pattern probably won't stay the same over time.

"Everybody agrees that spirals are density waves," says Sellwood. "It's just what causes them, how long they last — that's what we're arguing about."

What Creates Spiral Arms?

If spiral patterns are short-lived, then why do we see them everywhere we look? Answering that question comes down to understanding what launches the waves to begin with. Whatever that mechanism is, it must be universal enough to explain most, if not all, spirals we see.

Take the fluffy flocculents, for example. Their pattern could start with a lump, such as a giant cloud that's beginning to condense into stars. Differential rotation will quickly shear any such lump into a spiral shape, creating a "wake" in the disk. The other stars in the disk then get in the game, interacting with the stars in the lump in a way that amplifies the little spiral by a factor of 100 or so. That region of enhanced density then becomes a density wave that sloshes through the disk.

This idea, known as *swing amplification*, has been around awhile. William Julian and Alar Toomre (also both at MIT) first proposed it in the mid-1960s, at around the same time as the density-wave theory. But in their study, they simplified complex mathematical equations in order to solve them with pen and paper, which ultimately dampened the pattern the process was meant to grow: The spirals in their calculations first expanded until they dominated their galaxies, but after a couple galactic rotations (perhaps half a billion years), the density waves faded away.

Decades later, D'Onghia and colleagues revived the idea in simulations with 100 million stars. This time they didn't have to simplify the math involved; the increased computing power worked through the equations. The team seeded this

many-starred disk with 1,000 larger objects the size and mass of star-forming clouds. These clouds quickly formed wakes that amplified into spirals, as they had in Julian and Toomre's studies. But to the researchers' surprise, the overall spiral pattern didn't fade away. Instead, one wake inspired another, which inspired another, until the simulation ended.

The spirals in these simulations, though, are not two sweeping arms that trace singular paths through the galaxy. There's no lasting global pattern at all. Instead, this process makes segments that join up to form a whole, constantly remaking the arms we see. We may always see a spiral, but it's not always the *same* spiral.

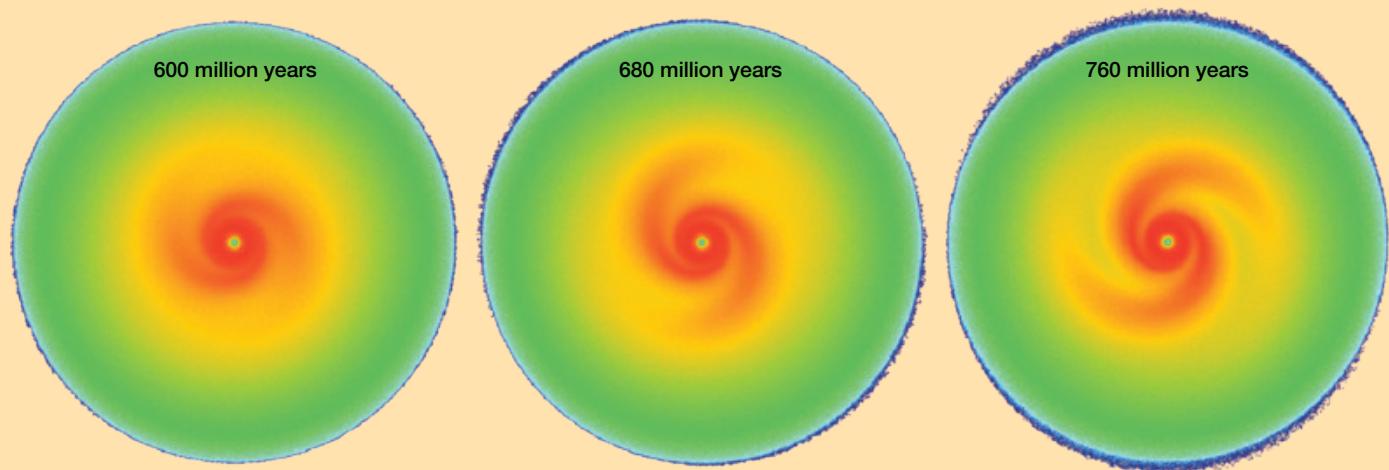
"Locally, these arms seem to fall down and reform," D'Onghia explains. "But they are long-lived statistically — that means that these patterns, once they form, they never disappear."

Some observations support the swing-amplification scenario, finding that flocculent-type galaxies tend to have kinks and changes in the angle of the spiral, which suggest the arms are made of multiple segments.

The arms, then, are almost an optical illusion. "We all evolved so we could see the stripes of the tiger in the jungle," notes Tremaine. "So your eye connects the [segments] and says, 'Oh, there's this beautiful big spiral pattern,' when it really is just a lot of bits and pieces."

D'Onghia's team made waves in the field when they published their update to the swing-amplification scenario. Many thought they had finally answered the question of what creates spiral arms. But not everyone agreed: Some wondered whether the complex simulations the team had run really represented the math better, or whether there were unintended numerical effects.

Sellwood, for one, doesn't think swing amplification by itself can fully account for actual spirals. He has a different idea, something he calls *groove modes*. In this case, there are



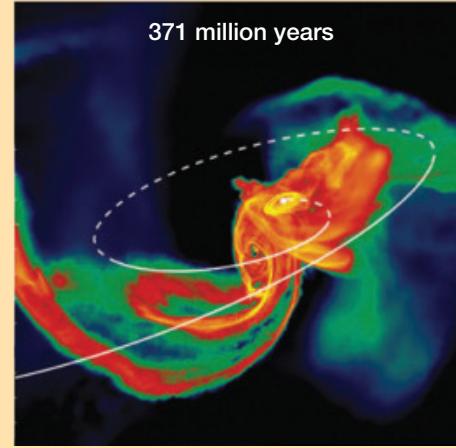
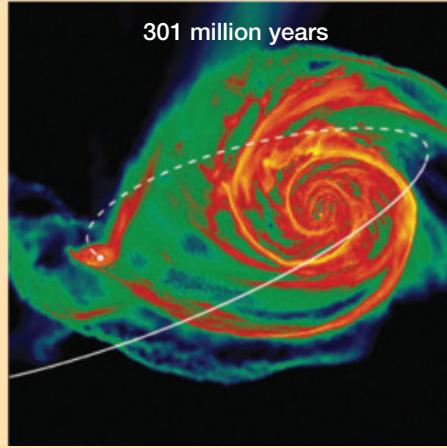
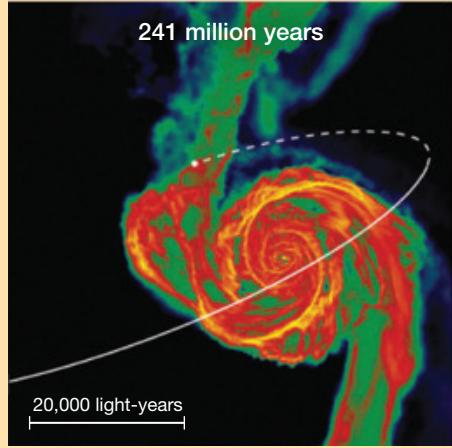
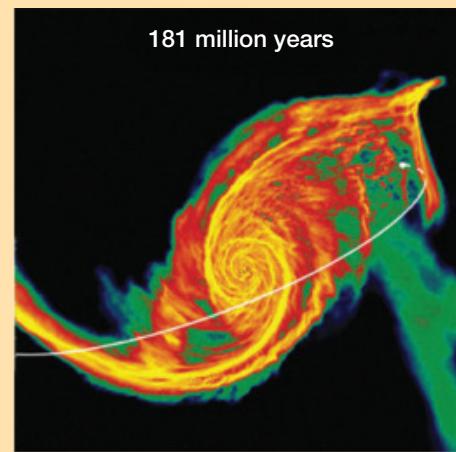
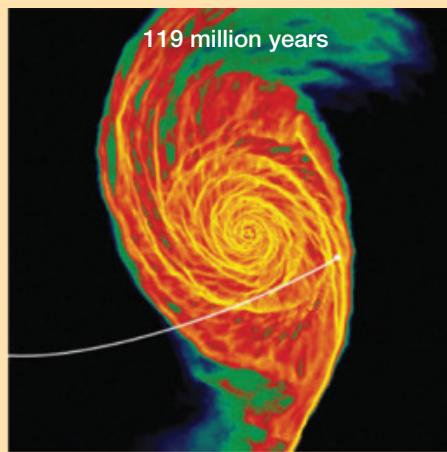
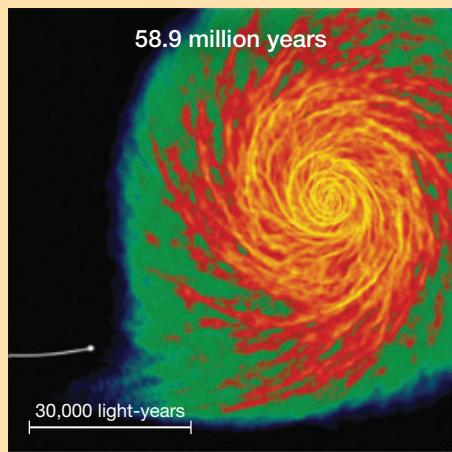
▲ **GETTIN' IN THE GROOVE** These frames of a different simulation show the development of spiral arms from a type of gravitational instability known as a *groove mode*. The spiral arms develop quickly, over tens of millions of years, and then rotate around. This simulation is simplified, showing only one groove mode in action; more typically, one such instability would generate another, and so on.

► THE WHIRLPOOL

In some cases, as for M51 and the smaller NGC 5195, a companion's tidal pull can spawn a grand-design spiral pattern.

▼ A COMPANION'S PULL

In computer simulations, shown here as six frames that cover several hundred million years, the galaxy NGC 5195 swoops in and around the larger M51. After some 300 million years (fifth frame), the smaller galaxy's tidal pull creates a grand-design pattern in the bigger galaxy that's remarkably similar to the real pattern observed in M51. Eventually, the larger galaxy will devour its companion, losing the grand sweep of its arms in the process.



gaps in the distribution of stars in the disk, rather than the massive clumps of D’Onghia’s simulation. Sellwood likens these gaps to the destabilizing effect of a scratch in a piece of glass. Stars and gas clump on either side of the gap, resulting in extensive spiral arms. As the arms decay, they “scratch” new gaps (and associated clumps) elsewhere, causing additional spiral arms to form.

Both swing amplification and groove modes use gravitational instabilities to explain spiral patterns in isolated galaxies, but in different ways. “Probably the right way to think of the swing amplification is as a transitory event that makes the instabilities much stronger than you would otherwise think,” Tremaine suggests. “The groove instability is a kind of self-propagating cycle of instabilities.” The two result in different spiral types: While swing amplification would only generate ragged, multiple-armed spirals, groove modes could reproduce the entire gamut of patterns.

Grooves and swing amplifications might also work in league with other gravitational exchanges. Some have suggested that bars — the elongated structures that skewer many spiral galaxies’ central bulges — can interact with the rest of the disk to drive a spiral pattern. However, bars’ gravitational effect is weak, and observations have shown most spiral patterns rotate at speeds different from the bar. So while these structures might have some effect, they’re probably not directly responsible for most spirals.

Companion galaxies, though, do drive spiral structure. When a dwarf satellite swings close by a disk galaxy, the two galaxies pull on each other. Like tides caused by the Moon on Earth, the pull of the smaller galaxy stretches both the near- and farside of the larger one, driving the creation of two grand arms.

Theorist Clare Dobbs (University of Exeter, UK) led a team in simulating the evolution of the Whirlpool Galaxy as it interacts with its companion NGC 5195, recreating it almost exactly. “The simulation produced some quite detailed kinks in the spiral arm,” Dobbs says. “I hadn’t expected it to reproduce the observations quite that well.”

Perhaps interacting with companions could explain *all* grand-design spirals. After all, muses Karen Masters (Haverford College), “is it really the case that there are any isolated galaxies?” Cosmological simulations suggest there are still a lot of smaller clumps in the universe, whether of stars or dark matter, so no galaxy is an island entire of itself. “Maybe,” Masters suggests, “you don’t need a way to make grand-design arms in an isolated galaxy.”

And maybe every one of these processes is at work. “I don’t necessarily think that there is one cause of spiral structure,” Dobbs says. “Gravity is the underlying force, but there are different ways that spiral structure can come about.”

What Spiral Arms Do

Spirals, whether flocculent, multi-armed, or grand-design, are more than just pretty. The patterns contribute to lasting change in their galaxies. But they’re not always appreciated

as such. “I think a lot of astronomers just don’t even really think about spiral arms very much,” Masters says. “They’ll write papers about spiral galaxies and not mention spiral arms and the impact they might have.”

Spiral arms’ most obvious impact is the stellar nurseries that they foment: The density waves sloshing through the disk compress gas and ignite these new stars. The waves also compress, and thereby amplify, magnetic fields, which help regulate star formation.

A more subtle effect is the rearrangement of the galaxy’s stars. As arms sap angular momentum from the inner regions, transferring it to the outer parts of the galaxy, stars can surf the spiral and move inward, Masters says. As a result, the bulk of a galaxy’s spinning material moves toward its core over time, while a much smaller amount of material in the outskirts expands.

But this transfer of energy can shuffle stellar orbits in complex ways, Tremaine adds, causing stars to migrate back and forth relative to the galactic center. The Sun, in fact, most likely began its life closer to the center: The amount of heavy elements in our galaxy’s star-forming gas generally increases inward, and the Sun’s composition corresponds to a birthplace as close as 16,000 light-years from the core. Today, it’s 10,000 light-years farther out.

“That shuffling is almost certainly caused by spiral arms,” Tremaine says. “We’re only just beginning to understand how strong that process is and what effects it had on the galaxy.”



▲ **INVISIBLE ALIGNMENT** Using a far-infrared camera aboard the Stratospheric Observatory for Infrared Astronomy, astronomers revealed the magnetic field of the spiral galaxy M77. The gravitational forces that created M77’s shape are also compressing its magnetic field lines, so that the streamlines follow the arms (underlying image).

A Complicated Case

To understand the origin of spiral arms, one would be forgiven for thinking our own would be the easiest example to study. After all, it's right here in front of us. But history has shown otherwise.

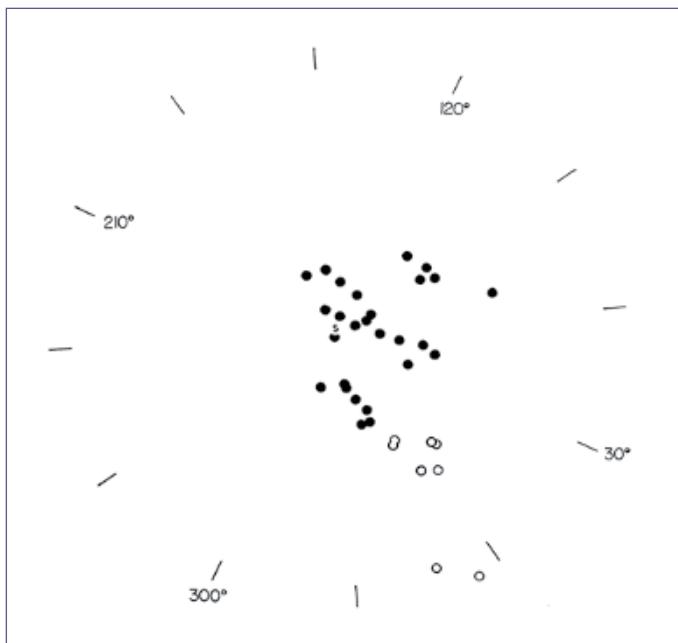
The first firm evidence for our galaxy's spiral structure came in the 1950s, as William Morgan (Yerkes Observatory) mapped distances to the most massive, and thus the most short-lived, stars (S&T: Feb. 2023, p. 30). The three stripes these stars depict were later named the Perseus, Orion, and Sagittarius arms.

But initially, observations of these arms showed only stumps — it wasn't clear how far around the galactic center they wound. Later, maps based on the distribution of hydrogen gas added to this first crude picture. And later still, further improvements came from increasingly precise measurements of distances to millions of massive, young stars and even protostars.

Those improvements didn't come easily, though. "There were a lot of arguments with a lot of egos," says Robert Benjamin (University of Wisconsin, Whitewater). "And not enough data to really distinguish between different points of view."

Even now, there's still much debate when it comes to the Milky Way's appearance. The points of contention played themselves out when astronomer and graphic artist Robert Hurt (Caltech) attempted to visualize the Milky Way in 2008. The concept depicted a four-armed spiral, with two of the arms more prominent.

Benjamin, one of the astronomers who contributed to that visualization of the Milky Way, says he received pushback when it came out. Are there *really* four arms, or just two? Do



▲ **THE FIRST MAP** Published in 1953, this initial map of star-forming regions in the Milky Way presents three stripes, hinting at spiral structure in our galaxy. Later observations of stars and gas bore this conclusion out.

Density Waves

In the classical scenario of density waves, spiral arms are persistent patterns. Stars form in arms but ultimately pass through them, while the pattern itself continues on. Watch a rendering of classical density-wave theory at <https://is.gd/DensityWaves>.

two really dominate, or are all four equal? Some even argued over whether the Milky Way is a spiral at all.

“I was just trying to make a nice, public-friendly artist’s picture that incorporated the data,” Benjamin says. “I did not intend for it to be in the *Astrophysical Journal*. It sort of became a default by accident, because people just needed to grab something.”

The visualization has remained the default even though other teams, and even *Sky & Telescope* (S&T: Nov 2019, p. 16, reproduced on next page), have sought to refine the picture. “My hope is to see it replaced in the next few years – then I will be free of this burden,” Benjamin adds, laughing.

Understanding the shape of our own galaxy is difficult in part because we're looking at the whale from inside its belly. Our position in the galactic plane complicates distance measurements, as does the dust that obscures our view of the other side. Even the Gaia space telescope's extremely precise distance measurements to more than 1 billion Milky Way stars only extend to some tens of thousands of light-years from the Sun — a few tenths of our galaxy's diameter.

Besides the difficult-to-make measurements, the Milky Way is also far from an isolated and clear-cut example of a spiral. Evidence shows recent interactions with a massive dwarf galaxy, plus there's a bar at our galaxy's center with its own subtle effects.

The nature of the Milky Way spiral complicates matters, too. "If you don't have grand-design spiral structure, then the number of arms that you count is likely to depend on which patch of the galaxy you're looking at," Tremaine says. "My guess is that the right answer is that it's not really a question you want to ask."

Benjamin, too, takes an agnostic approach. "We rely on models to try to come up with a synthesis of our data," he says. "And then we forget the data." Ultimately, the data are what we have to go back to, he adds. And because the case of the Milky Way is so complex, he thinks it's not a great proving ground, at least not yet. "If you don't know which model to apply, I'm not sure the Milky Way is going to tell you which one is right."

Sellwood disagrees, arguing that *only* the Milky Way will provide data detailed enough to differentiate between spiral-launching scenarios.

To get a bigger and sharper picture of our galaxy, and thus an improved testbed, astronomers have added other methods of mapping the Milky Way. One of these is distance measurements to *masers*, warm, radio-emitting gas associated with

1,000-year-old O and B stars. Two surveys, the American-based Bar and Spiral Structure Legacy (BESSEL) and Japan's VLBI Exploration of Radio Astrometry (VERA), use these freshly minted massive stars to precisely trace the spiral structure over about half of our galaxy. (The farside is still largely out of reach because the masers become too faint to accurately measure.)

The Sloan Digital Sky Survey, or SDSS (S&T: Jan. 2023, p. 20) also contributes to the effort by mapping stellar motions and compositions. For example, when groups of stars move together, astronomers generally surmise they were born together. But knowing their composition can tease apart the their birth group from other effects.

"Sometimes stars tend to have similar motions not because they're born together, but because they feel the same influence from the arms," D'Onghia says. "With the Gaia era, and SDSS V, we will learn a lot about where these regions are, where such resonances happen."

Here, There & Everywhere

Perhaps the best way to test spiral scenarios is a both/and approach. "You can get much more information about the Milky Way," Master says, "but the Milky Way is just one example of a galaxy."

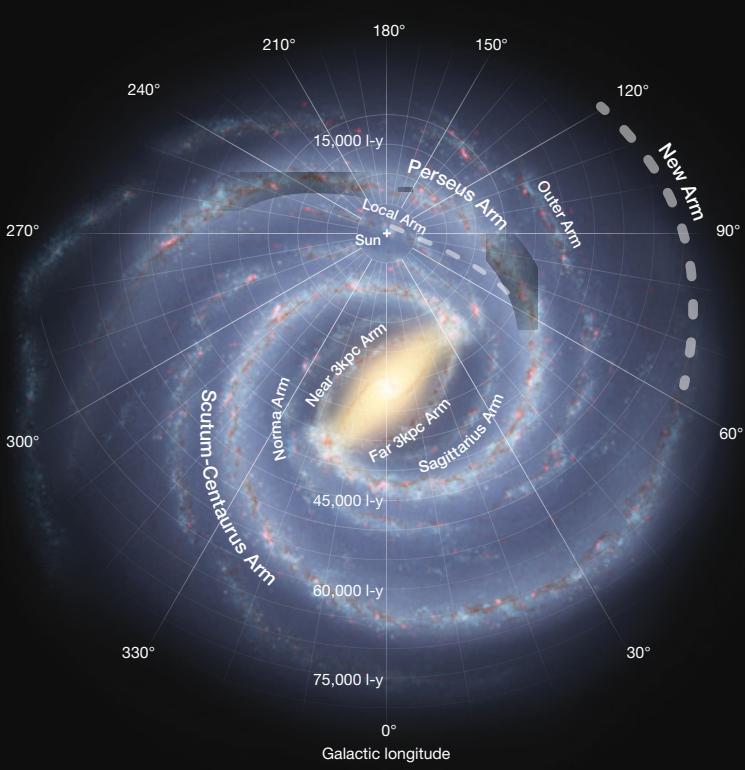
Other galactic examples are, of course, far away and thus much fainter, but they win in terms of sheer number and

variety. Legions of citizen scientists participating in Galaxy Zoo (galaxyzoo.org), of which Masters is the principal investigator, have classified millions of galaxy images. Over the past 15 years, this web-based project has advanced from simply classifying galaxy type (e.g., spiral vs. elliptical) to identifying more complex properties, such as how tightly spiral arms are wound. Astronomers have used these detailed data to test — and overturn — predictions.

Nor are spirals limited to the relatively nearby universe; we see them almost as far back as we can see disks. In one of the most distant examples, Takafumi Tsukui and Satoru Iguchi (both at SOKENDAI, Japan) used the Atacama Large Millimeter/submillimeter Array in Chile to image the spiral shape of a galaxy that existed just 1.4 billion years after the Big Bang. The newly operational James Webb Space Telescope, or JWST (S&T: Nov. 2022, p. 12), could also reveal spirals in the early universe, when galaxies were first emerging. "This is the new challenge, trying to see when they form these features," D'Onghia says.

With insights now coming in from a multitude of sources, a field that was once starved of data is now swimming in it. "It's a very exciting time, and it's a complicated time," Benjamin says. "But at least we have a lot more data to work with."

■ News Editor MONICA YOUNG practiced making cream spirals in many coffees while writing this article.



▲ **FROM ABOVE** These two images conceptualize what the Milky Way would look like from the outside, each one based on multiple datasets. Depending on how the data are analyzed, interpreted, and prioritized, different views of our galaxy are possible.



Appreciating Earthshine

This subtle celestial spectacle is not only a wonder to behold, it also has some surprising uses.

The pale glow of the Moon's nightside nestled between the horns of its narrow sunlit crescent is always a favorite spectacle for naked-eye skywatchers on crisp, clear evenings. The evocative French term for this ghostly light is *la lumière cendrée* or "the ashy light," while in Britain it is popularly referred to as "the old Moon in the new Moon's arms."

Through binoculars, earthshine lends the Moon an inef-fably three-dimensional appearance. The dappled pattern of dusky lunar "seas" and the bright rays associated with the craters Tycho, Copernicus, and Kepler are distinctly visible, while the brilliant crater Aristarchus glows like a tiny ember.

Seeing the Light

Greek astronomer Posidonius, widely regarded as the most learned man of his era, attributed earthshine to the partial transparency of the lunar globe that allows some

sunlight to pass as if through a translucent cloud. Others conjectured that the Moon was faintly self-luminous or phosphorescent.

In his treatise about eclipses published in 1596, Johannes Kepler's teacher and mentor Michael Mästlin correctly stated that earthshine is sunlight that has been reflected first by the Earth and then by the Moon before reaching our eyes. The versatile Renaissance genius Leonardo Da Vinci had offered the same explanation for the Moon's "secondary light" almost a century before Mästlin, but his priority for this insight was all but forgotten until his notebooks were published in 1797.

▲ **SUNLIGHT AND EARTHLIGHT** Extremes of brightness pose a daunting challenge when capturing images of earthshine. This beautiful photo of a waning crescent Moon is a composite of two images, one properly exposed for the sunlit portion, the other for the earthlit portion.

In his 1610 pamphlet *Sidereus nuncius* (*The Starry Messenger*), Galileo explained that Earth's phase in the lunar sky is always the exact opposite of the Moon's phase in our sky. When the Moon is new Earth is full, and when the Moon is a crescent, Earth is gibbous. He noted that earthshine is brightest when the Moon is a narrow crescent close to the rising or setting Sun and "diminishes more and more as the Moon recedes from that body until, after the first quarter and before the last, it is seen very weakly and uncertainly even when observed in the darkest sky."

Galileo advised prospective earthshine observers to allow the Sun to sink as far below the horizon as possible and to interpose a chimney or roofline to block the glare of the bright crescent. From the Northern Hemisphere, the best viewing opportunities occur just after sunset during spring and just before sunrise during autumn, when the lunar crescent rides highest in the sky.

Earthshine on the Moon is far more intense than moonlight is on Earth. Our home planet occupies an area of the lunar sky more than 13 times larger than the Moon takes up in our sky, and on average Earth reflects almost three times more sunlight per unit area than the Moon. From a lunar vantage point, the full Earth appears 40 times brighter than the full Moon appears on Earth.

A 1991 NASA study entitled "Lighting Constraints on Lunar Surface Operations" found that the maximum and minimum intensities of earthshine on the lunar surface correspond to the illumination provided by a 60-watt bulb at distances of 2.2 to 4.9 meters (7 to 16 feet), respectively, sufficient for future astronauts to read checklists and conduct routine operations on the lunar surface. Nevertheless, this light level is very feeble compared with the brightness of the sunlit portion of the Moon, which is more than 10,000 times brighter.

The Apollo astronauts observed the lunar surface under a wide variety of lighting conditions. John Young, who flew on two Apollo missions, was surprised that he could discern features on the Moon's earthlit surface as easily as in direct sunlight. Flying rapidly across the terminator, he was able to pick out a wealth of topographic detail and surface texture in earthshine-illuminated moonscapes long before his eyes were fully dark adapted.

A Measure of Illumination

The brightness of earthshine varies dramatically depending on the reflective properties of the side of Earth facing the Moon. *Albedo* (from the Latin for "whiteness") is the fraction of incident light reflected by a surface. *Geometric or normal albedo* is a measure of the reflectivity of a surface that's illu-

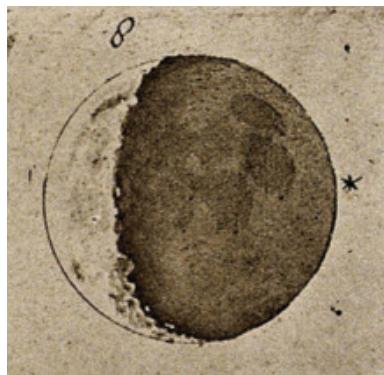
minated and viewed vertically, with the light source located directly behind the observer. It's measured on a scale ranging from 0.0 to 1.0, with 0.0 corresponding to a surface that absorbs all incident light, and 1.0 denoting a surface that reflects all incident light.

Freshly fallen snow has an albedo of 0.9; bare sea ice 0.5 to 0.7; the dense cumulonimbus clouds of a thunderstorm 0.7 to 0.9; the low stratus clouds of an overcast day 0.4 to 0.6. These are Earth's most reflective features. The albedo of desert sands ranges from 0.3 to 0.4; dry grasslands 0.2 to 0.3; dense forests 0.1 to 0.2. Open bodies of deep water are by far the darkest areas, with an albedo of only 0.06.

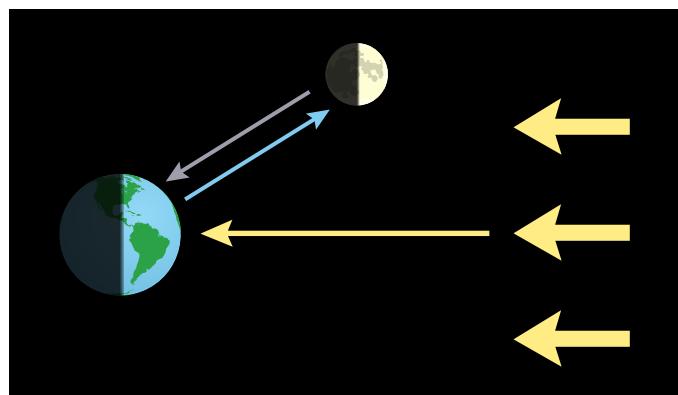
For observers in eastern and central North America, the waning crescent Moon in the predawn sky receives light reflected by the relatively bright continental landmasses of Africa and Eurasia, while the waxing crescent Moon in the evening sky receives light reflected by the vast expanse of the dark Pacific Ocean. Consequently, earthshine on the waning crescent tends to be brighter than on the waxing crescent, although the extent of cloud cover has a much more profound

effect. On average, clouds account for two-thirds of the light reflected by Earth, making meteorology far more important than geography in determining the visibility of earthshine.

On the evening of March 29, 2009, several veteran observers in Britain were struck by the extraordinary brightness of earthshine on a three-day-old Moon. One of them, Nigel Longshaw, reported in the April 2010 issue of the *Journal of the British Astronomical Association*: "I cannot recall ever seeing so many identifiable features on the earthshine portion of the Moon in the past." Noting that heavy snowfalls prevailed over much of the eastern and central United States



▲ **FIRST TELESCOPIC VIEW** Rendered by Galileo himself, this watercolor of the Moon on the evening of November 30, 1609, depicts the appearance of earthshine through his primitive telescope.



▲ **TWICE-REFLECTED SUNLIGHT** Our ability to see the "unlit" portion of the Moon is the result of sunlight reflecting off our planet, then bouncing off the Moon and back to Earth. S&T lunar columnist Charles A. Wood accurately dubbed this "twice-reflected sunlight," but it's better known as earthshine.

on that date, he wondered: "Might it have been these heavy snow-laden clouds which had some effect on the intensity of sunlight reflected toward the Moon, perhaps contributing to the prominence of earthshine visible in the UK evening sky?"

The first weather satellite became operational in 1960 when NASA lofted *Tiros 1* into orbit. However, the notion that the Moon might allow us to monitor Earth's weather dates back to a paper presented to the Paris Academy of Sciences in 1833 by the director of the Paris Observatory at the time, François Arago. He pointed out that the brightness of earthshine should be enhanced by widespread cloudiness on Earth and suggested: "When we have better photometric instruments at our command, we may be able to read in the Moon the record of the average clearness of our atmosphere."

A quarter of a century later Arago's prophecy was echoed by the German explorer and naturalist Alexander von Humboldt in his multi-volume treatise *Kosmos*: "It is therefore not impossible, notwithstanding the surprise which such a result might excite on first view, that one day meteorologists will derive valuable ideas as to the *mean state* of the diaphany [transparency] of our atmosphere in the hemispheres which successively contribute to the production of the ashy light."

Upon Reflection

The improved photometric instrument that Arago hoped for was devised in the 1920s by his countryman André-Louis Danjon. Ingenious yet elegantly simple, Danjon's design employs a pair of right-angle prisms to produce a double



▲ **EXTREMES OF REFLECTIVITY** This 1968 photograph of Earth by the Apollo 8 astronauts shows the dramatic differences in the brightness of clouds, land, and water. Nearly all of South America was overcast except for the Andes Mountains along the Pacific coast. A small portion of cloud-free western Africa is also visible along the evening terminator.

image. One prism is mounted centrally in front of the objective lens of a small refracting telescope, the other off to the side. By adjusting the radial orientation and distance between the prisms, the observer can see a pair of adjacent lunar images, with the dark earthlit limb of the first image just touching the bright sunlit limb of the second.

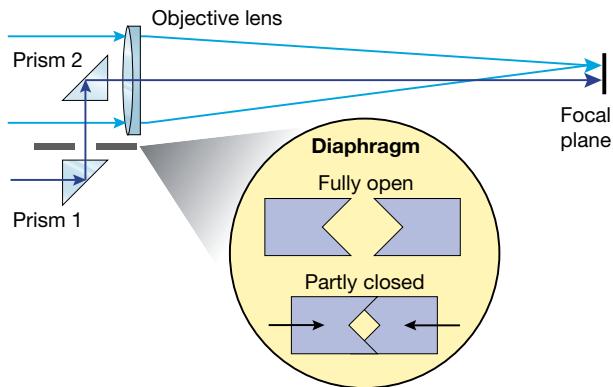
To attenuate the brightness of the second image, a cat's-eye diaphragm is interposed in the light path of one of the prisms. This clever device consists of a pair of overlapping rectangular metal plates with opposing ends notched with a V profile. Rack-and-pinion gears impart equal but opposite motions to each plate. As the plates slide together, a square aperture of constantly decreasing area is formed, allowing the second image to be dimmed. The aperture of the diaphragm is read on a calibrated scale. The juxtaposed double image eliminates errors introduced by atmospheric extinction and scattered light from the luminous veil of the twilight sky.

By reducing the brightness of the Moon's sunlit limb until it appears equal to the brightness of the earthlit limb, the observer can determine the intensity of incident sunlight relative to the intensity of earthlight. Earth's planetary albedo or overall reflectivity can be extrapolated from this ratio with a high degree of precision.

Danjon used his portable earthshine telescope to make over 200 measurements of earthshine intensity between 1926 and 1935. His observing program was resumed by Jean Dubois at Bordeaux Observatory in 1940 and continued until 1960. These early studies revealed that the brightness of earthshine



▲ **A DISTANT MIRROR** When we view a thin, earthlit Moon, an observer on the lunar surface would be presented with the inverse phase on Earth, resembling the photograph at left. This inverse relationship partly explains why earthshine fades as the Moon waxes, since the amount of light reflecting off our planet is diminishing as Earth's phase wanes, thereby reducing the amount of reflective surface area.



▲ **SIMBLE BUT PRECISE** André-Louis Danjon's earthshine telescope used a pair of prisms to provide two identical side-by-side images of the Moon, as shown in the illustration at right. A cat's-eye diaphragm could be adjusted to dim one of the images until the Moon's sunlit portion had the same apparent brightness as the earthlit portion of the unadjusted image.

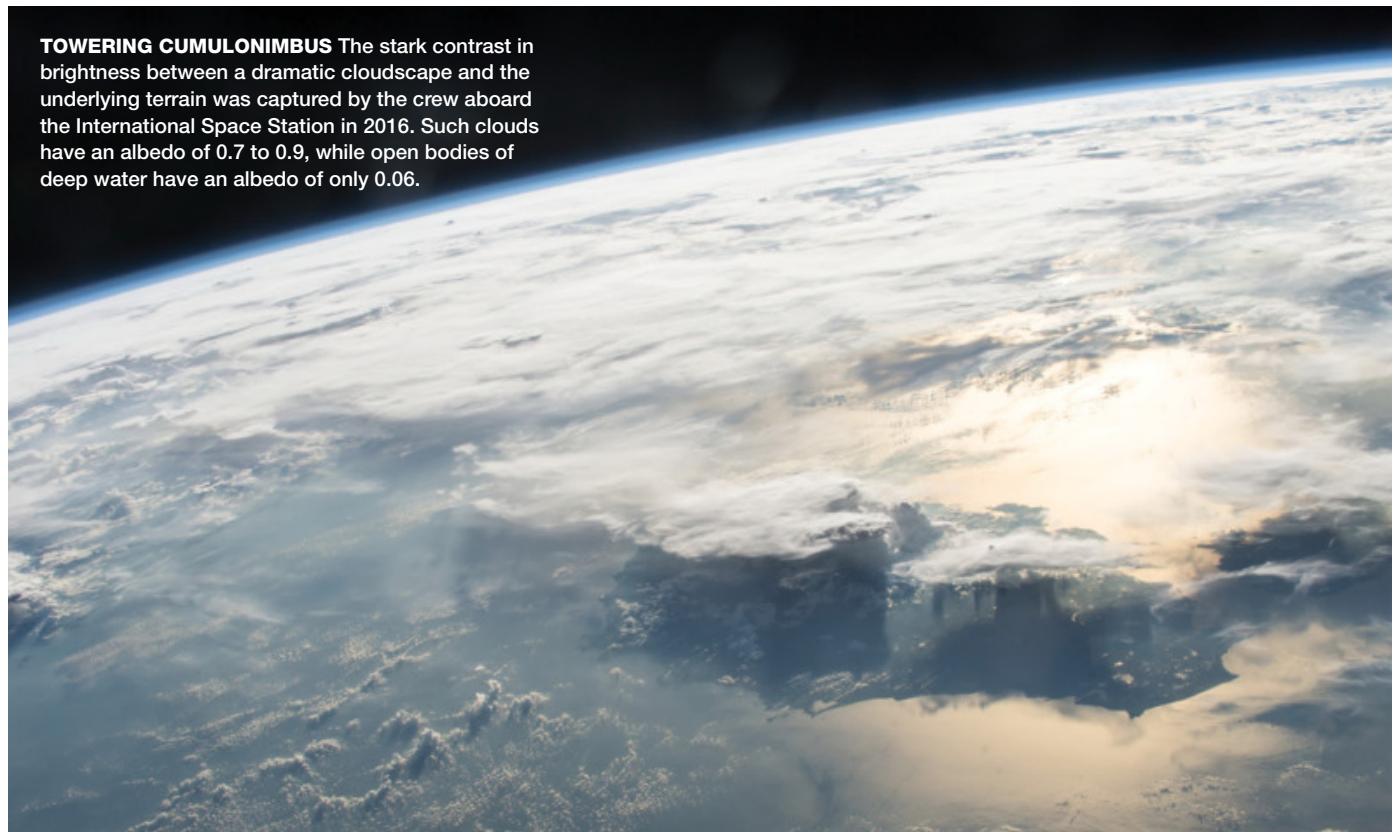
varies not only daily due to changes in cloud cover, but also seasonally (faintest in August and brightest in October) and even from year to year.

Observing only from sites in France, Danjon and Dubois derived values for Earth's albedo that were erroneously high because the comparatively bright Eurasian landmass to their east reflected more sunlight onto the Moon than the oceans did. To eliminate this source of error, during the 1950s and 1960s Harvard College Observatory astronomer Fred Whipple and Gustav Bakos of the University of Waterloo in Canada independently established global networks of Danjon earth-

shine telescopes at sites widely separated in longitude. Bakos soon discovered a second source of error: the brilliant specular reflection of the Sun off the surface of Earth's oceans when overlying clouds are absent. This sun glint can brighten earthshine considerably.

The third and largest source of error in the pioneering French work proved to be the extremely nonlinear variation in the reflectivity of the Moon as its phase changes. At full Moon, the brightness of every point on the entire lunar surface shines a whopping 40% brighter than just one day earlier or later. This is caused by a phenomenon known as *coherent*

TOWERING CUMULONIMBUS The stark contrast in brightness between a dramatic cloudscape and the underlying terrain was captured by the crew aboard the International Space Station in 2016. Such clouds have an albedo of 0.7 to 0.9, while open bodies of deep water have an albedo of only 0.06.





▲ **FATHER OF EARTHSHINE SCIENCE** After serving as a highly decorated infantry officer in the First World War, André-Louis Danjon (1890–1967) emerged as a towering figure in 20th-century French astronomy. In addition to his pioneering studies of earthshine, he devised a useful five-point scale to describe the appearance and brightness of the Moon during total lunar eclipses.

backscattering, first observed in the early 1980s by experimental physicists shining laser beams into turbid liquids. At very narrow angles of incidence, reflected light is enhanced when it strikes a microscopically rough surface covered with minuscule grains comparable in size to the light's wavelength. Provided that the distance between the particles is greater than one wavelength, light rays tend to scatter in a backward

direction and combine by constructive interference with incoming rays to produce an amplified reflection.

Using a huge mass of data accumulated since the 1970s by satellites in low-Earth orbit, scientists currently estimate Earth's average albedo at 0.30, significantly lower than the value of 0.39 Danjon published in a 1936 summary of his work. Ironically, eight years earlier he had advanced a far more accurate value of 0.29 but revised it upwards based on a faulty model of the variation of lunar reflectivity with phase.

Signs of Life

Interest in the earthshine method of monitoring Earth's albedo revived in the 1990s as the issue of climate change took on unprecedented urgency. In the broadest sense, three major factors contribute to changes in climate: changes in the amount of sunlight Earth reflects back into space; changes in the energy output of the Sun (which only varies by about 0.1% during a typical 11-year activity cycle); and changes in the amount of greenhouse gases in Earth's atmosphere that trap heat.

In an article appearing in the winter 1994 issue of *Engineering & Science*, California Institute of Technology physicist Steven E. Koonin cited the limitations of satellites for measuring variations in Earth's overall reflectivity:

They cannot cover large areas of the globe simultaneously (just patch by patch), nor can they do so continuously; any one satellite sees a given point on Earth only infrequently . . . It's also not so easy to keep a precision instrument calibrated in



EARTHSHINE FROM ORBIT The International Space Station is an unsurpassed vantage point for observing earthshine. A thin lunar crescent hovers just above our planet's twilight limb in this 2011 photograph.

space. As a result, two different satellite systems will typically differ by 0.7 percent in the monthly average albedo. That may not sound like much, but it's worth about 1.5 degrees in the global temperature, a non-negligible fraction of the expected greenhouse warming. Satellites are also expensive — typically costing hundreds of millions of dollars — and they can break . . .

Koonin noted that, in addition to being very inexpensive, ground-based earthshine measurements are self-calibrating and automatically integrate the reflectivity of a large portion of the planet. Earthshine data also promised to be very valuable for precisely calibrating satellite instruments.

In 1998 a team of investigators led by Philip Goode of the New Jersey Institute of Technology began to regularly monitor the brightness of earthshine at the Big Bear Solar Observatory in California. The NASA-funded Project Earthshine acquired almost 1,500 nights of usable data by the end of 2017. As noted by Goode and his collaborators in an article appearing in the May 2004 edition of *Science*, these measurements compare favorably with simultaneous satellite observations of global cloud cover from the International Satellite Cloud Climatology Project and indicate that “Earth’s reflectance as measured from earthshine is noticeably variable on monthly, yearly, and decadal scales, with a net over sixteen years that is essentially nil.”

The three most recent years of data indicate a very modest decline in global albedo that may be related to a decrease in bright, low-lying clouds over the warming waters along the Pacific coast of North and South America. No correlation was found between changes in terrestrial albedo and sunspot number, cosmic ray flux, or other solar-activity indices.

In addition to its usefulness in investigating climate change, earthshine points to a method of detecting life on distant worlds. Chlorophylls, the pigments that power photosynthesis, efficiently absorb light over much of the visible region of the spectrum but are highly reflective in near-infrared light. This abrupt increase in reflectivity at a wavelength of 720 nanometers produces a characteristic spectral signature known as the “red edge.”

Phytoplankton in the oceans do not produce this signature because seawater is a strong absorber of red and near-infrared light. However, they do show a peak in reflectivity at 550 nanometers that gives phytoplankton-rich waters a distinctive greenish hue.

In 2001 both the “red edge” of vegetation-covered land and the green fingerprint of ocean phytoplankton was detected in low-resolution spectra of earthshine obtained with the 2.3-meter (90-inch) Bok Telescope on Kitt Peak by University of Arizona astronomers Neville Woolf and Paul Smith. They noted that an alien observer would have seen the green phytoplankton signal appear in the spectrum of Earth about two billion years ago. The red edge feature would only have been present after extensive plant cover on land developed about 440 million years ago. Astrobiologists are keen to look for these biosignatures in the spectra of exoplanets.



▲ **SEEING THE INVISIBLE** The “red edge” spectral signature of chlorophylls causes foliage to appear brilliant white in this photograph of a cypress tree and grasslands taken through a near-infrared filter that blocks visible light.



▲ **LIFE FROM SPACE** Fed by nutrient-rich urban and agricultural runoff, a bloom of phytoplankton appears as bright swirls in this satellite image showing the waters off the Russian Black Sea port of Novorossiysk in the spring of 2013.

With the Moon serving as a distant mirror, earthshine provides a cosmic perspective. “Even the spectrum of Earth by the Galileo spacecraft, made by Carl Sagan and colleagues in 1993, was just a small region of ocean,” Woolf noted in the online magazine *Wiley Analytical Science*. “It is possible to use the Moon to integrate light from the Earth and to determine what the spectrum of the Earth would be like if it were seen from far away as a planet. We need this information to prepare to observe Earth-like planets around other stars.”

■ Contributing Editors **TOM DOBBINS** and **BILL SHEEHAN** frequently write about the history of observational astronomy. Together they authored the widely acclaimed 2001 book, *Epic Moon: A History of Lunar Exploration in the Age of the Telescope*.



Dust in the Southern

Look toward Monoceros to find an eclectic collection of bright and dark nebulae.

My first telescope was a 2-inch f/8 Tasco refractor, which I enjoyed pointing at different kinds of nebulae. But the message I heard from more experienced observers was that if I was going to see much of anything, I'd have to spend a significant amount on a larger telescope. I didn't have that kind of money, so instead I invested in a 40-mm Kellner eyepiece that produced a 4° field of view and a magnification of 10×. The other half of my solution was very dark skies deep in the Kansas Flint Hills. Together, these delivered a limiting magnitude of around 12.8.

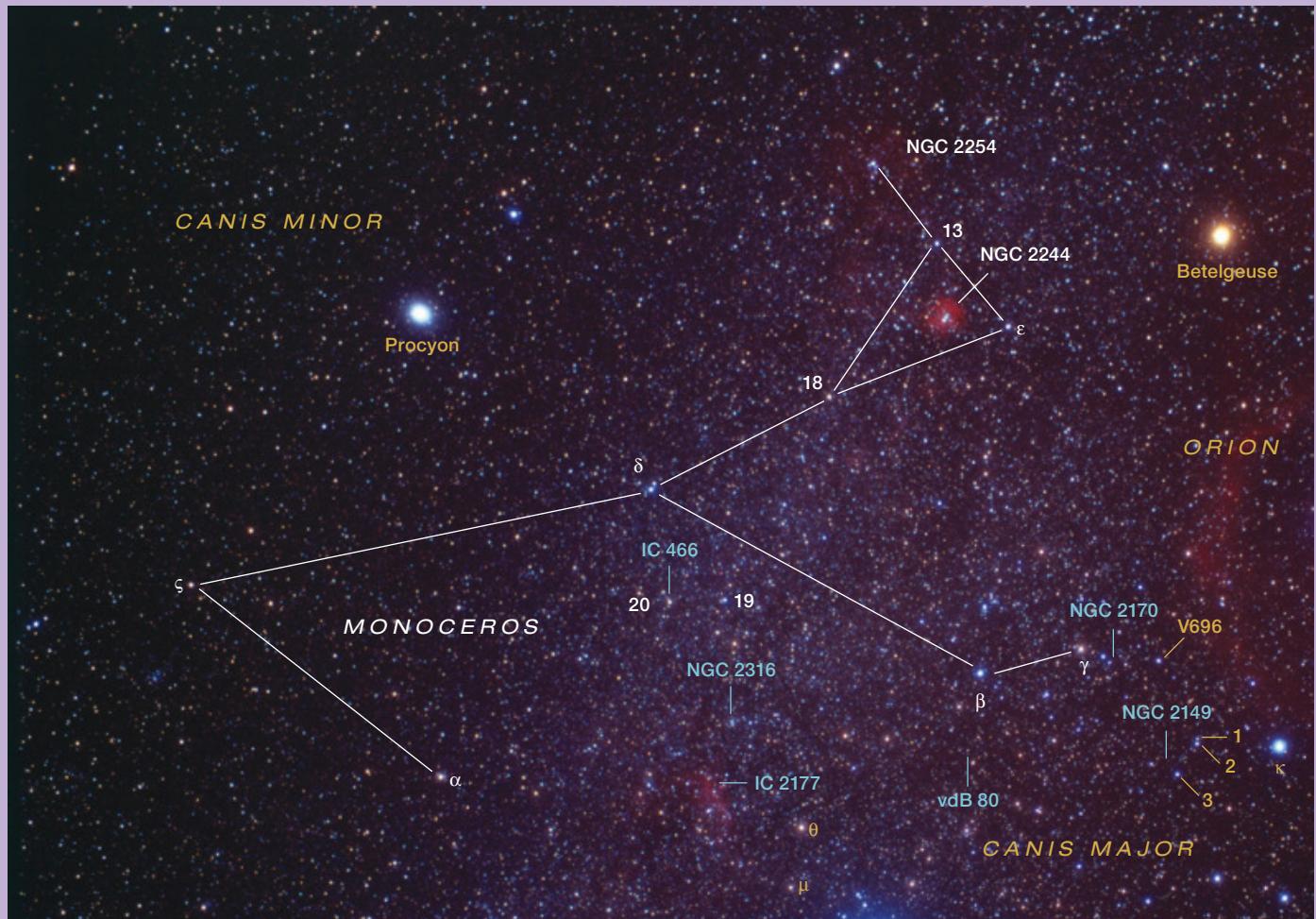
One winter I decided to explore the southern regions of the constellation Monoceros, the Unicorn. Starting with just about everybody's favorite object, the Orion Nebula (M42), I scanned east some 8° and came to a distinctive area

between the 5th-magnitude double star V696 Monocerotis and 4th-magnitude Gamma (γ) Monocerotis. Switching to my 20-mm Kellner eyepiece (2° field of view, magnification 20×), I was stunned by an obvious string of bright nebulosity. Intrigued, I decided to explore the region more thoroughly.

Reflection Nebulae for Small Telescopes

On my next visit to the area, I was armed with my 12-inch f/5 Dobsonian reflector and several eyepieces: a 32-mm Orion Q70 (47×), 15-mm Omegon Panorama² (100×), 11-mm Explore Scientific (131×), and 4.8-mm Televue Nagler (312×), along with top-quality 2× and 3× Barlow lenses. This scope and eyepiece set were a huge a step above where I started.

▲ **STEPPINGSTONE** As you sweep east from the nebulae in southwestern Monoceros, stop off at vdB 80, which is centered on two stars (9th and 10th magnitudes). Dark clouds to the west provide a dramatic backdrop. You'll find your target a bit less than 1/2° north-northeast of 6th-magnitude SAO 151573 (the bright star at the bottom of the frame).



Unicorn

Where southern Monoceros juts into Orion we'll find some very nice examples of bright and dark nebulae that can be appreciated in any telescope. Let's begin with the reflection nebula **NGC 2149**, which French astronomer Édouard Jean-Marie Stephan discovered in 1877. Locate 2nd-magnitude Kappa (κ) Orionis, also known as Saiph, and scan 4° east. Along the way, you'll encounter the 5th- and 6th-magnitude stars 1, 2, and 3 Monocerotis, arranged in a northwest-to-southeast line just 1° west of NGC 2149. In fact, these three stars also form the convenient border of a $60'$ -wide dark nebula involved with NGC 2149, which my 15-mm Omegon nicely framed. Until 1964, catalogs misclassified NGC 2149 as a galaxy due to the way it brightens toward its center.

About $3\frac{1}{2}^\circ$ north-northeast of NGC 2149 you'll find a wonderful set of reflection nebulae of various sizes involved in another large collection of dark clouds, **LDN 1644** to **LDN 1646**. American astronomer Beverly Lynds aggregated

dark nebulae into complexes to which she assigned ID numbers. The dark clouds are individually labeled and prefaced by LDN, which stands for Lynds Dark Nebula. Moving on to the bright clouds, the most prominent is **NGC 2170**, the westernmost of the bunch. William Herschel discovered it in 1784 and (mis-)cataloged it as the 19th object in his list of planetary nebulae.

NGC 2170, also known as the Angel Nebula, is centered on 10th-magnitude SAO 132861. Two other nebulae reside nearby. Scan a bit less than $9'$ east-northeast to find **vdB 69** (associated with 9.6-magnitude SAO 132868), and from there slew about $8'$ north to arrive at **vdB 68** (with its central star 9.7-magnitude SAO 132867). A nice little chain of 11th- and 12th-magnitude stars extends some $5'$ northeast of vdB 68. Each member of this group of bright nebulae surrounds 9th- and 10th-magnitude stars, which don't hinder the actual observation of the objects (see the image on page 31).

▲ **CLOUDS OF THE UNICORN** The faint constellation Monoceros features several well-known targets, such as the Christmas Tree Cluster (NGC 2254) and the Rosette Nebula (NGC 2244) in the northern reaches of the constellation. But there are other targets to explore, too. Southern Monoceros offers an eclectic collection of bright and dark nebulae — follow in the author's footsteps and spend some time there.



Slewing $\frac{1}{2}^\circ$ eastward from NGC 2170 you'll land on **NGC 2182**, **NGC 2183**, and **NGC 2185**, in that order. Herschel discovered NGC 2182 in 1786 and NGC 2185 in 1784 and cataloged both as planetary nebulae. (Later astronomers reclassified them as the reflection nebulae that they are.) Irish engineer and astronomer Bindon Blood Stoney first recorded NGC 2183 in 1850, but his position wasn't sufficiently accurate. Instead, credit for the object's discovery goes to German astronomer Heinrich Louis d'Arrest.

Pointing about 25' east-northeast of NGC 2170 you'll find NGC 2182, centered on the 9th-magnitude star SAO 132895. It's smaller than NGC 2170, but it's still easily visible and appears round in the eyepiece. Scanning an additional 20' east-northeast brings you to the nebulous pair of NGC 2183 and NGC 2185. Just south of a 12th-magnitude star and embedded within NGC 2185 lies an arc of 11th- to 12th-magnitude stars. All these targets were easy in my 2-inch f/8 Tasco, but if you have a bigger scope (like my 12-inch Dob), slide another 20' to 30' east of NGC 2185 to find **HH 271-273**, a collection of the more difficult *Herbig-Haro objects* (small, bright areas of nebulosity associated with newborn stars) embedded in the dark nebulae that comprise **Dobashi 1493**.

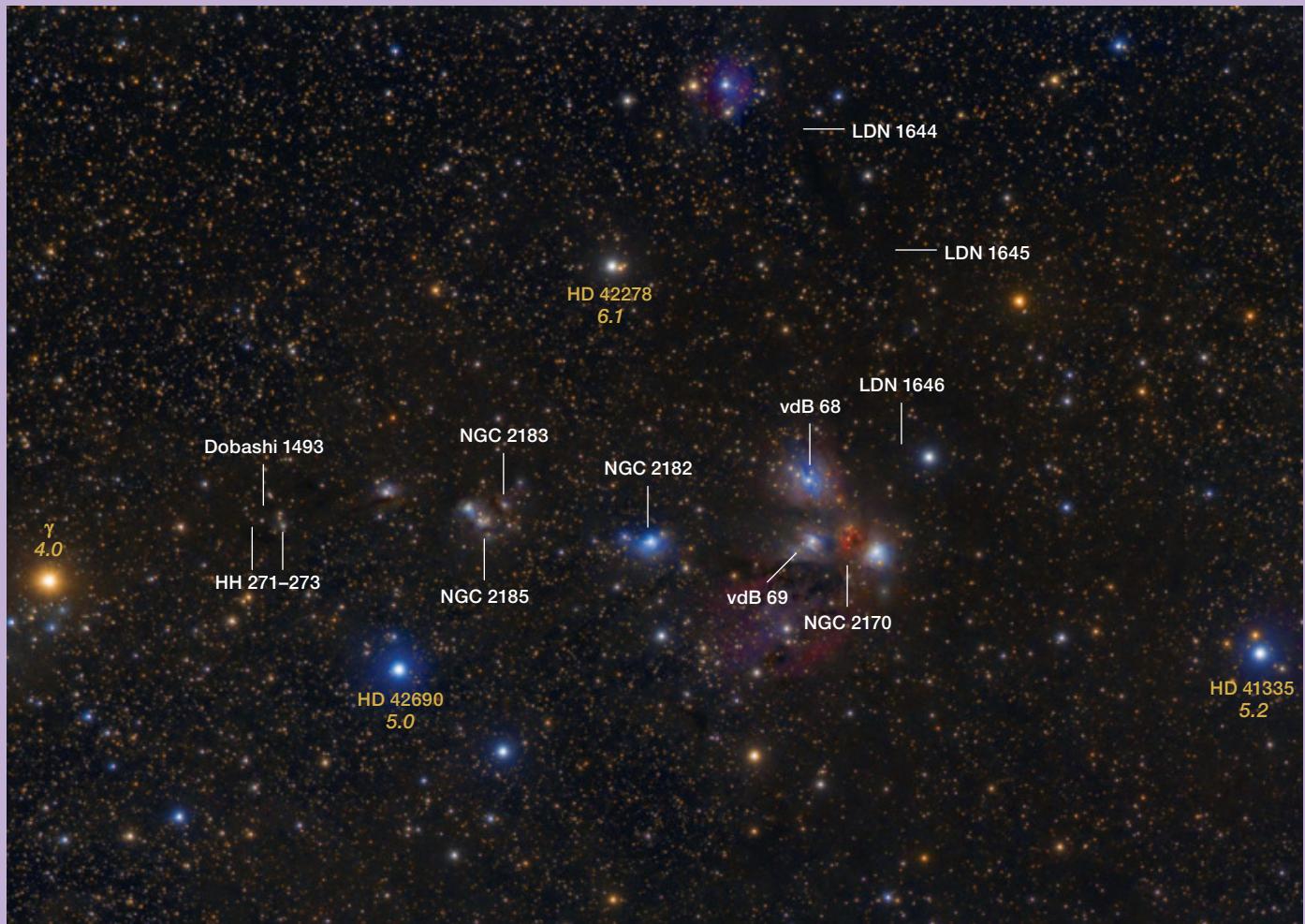
▲ **CONTRASTS IN LIGHT** A complex of dark nebulae spills over from Orion into Monoceros. We see the easternmost manifestation of the shadowy clouds on the western side of the reflection nebula NGC 2149. Two 11th-magnitude stars flank the nebula, one on its northwestern edge and the other south of its bright center.

Going a bit farther afield, some $6\frac{1}{2}^\circ$ southeast of the NGC 2170 group we find the complex target **vdB 80**. It's a bit fainter and smaller than the objects we already viewed.

Fainter Nebulae for Larger Telescopes

Now let's continue east and move deeper into Monoceros to find a group of isolated bright and dark nebulae. We begin with **NGC 2316**, about $7\frac{3}{4}^\circ$ almost due east of 3.7-magnitude Beta (β) Monocerotis. Herschel discovered the object in 1785 and cataloged it as the 304th object in his list of faint nebulae. A triangular grouping of 11th- to 13th-magnitude stars frames NGC 2316. The northern part of the nebula is concentrated and bright, but faint nebulosity envelopes the entire triangle of stars. An Ultra High Contrast (UHC) filter may help reveal this target. The dark clouds **LDN 1653** and **LDN 1654** extend about 16' north-northwest of NGC 2316.

A bit less than $\frac{1}{2}^\circ$ southwest of NGC 2316, we come to the smaller and fainter **NGC 2313**. The nebula, which



d'Arrest discovered in 1862, stretches north of its related star, 14th-magnitude V565 Monocerotis. The *Revised New General Catalogue of Nonstellar Astronomical Objects* erroneously lists the nebula as “nonexistent,” but it's not the first nor the only time the RNGC has misclassified an NGC object. Should you seek out this target, expect a difficult search that tests the limits of visibility. Try a UHC filter to improve your chances.

About $\frac{3}{4}^\circ$ southwest of NGC 2316 we find the faint and extended reflection nebula **DG 113**, which is involved with the 6th-magnitude star SAO 133937. The dark nebulae **LDN 1655** and **LDN 1656** spill to the south and southwest of the field. A bit less than $\frac{1}{2}^\circ$ west-northwest of DG 113, you'll find the fainter and more extended emission nebula **Sharpless 2-291**. Again, a UHC filter will aid in teasing out detail. Southeast of these objects and 55' southwest of the pretty star cluster M50 is the reflection nebula **vdB 87**. It's an easy object a few arcminutes west of a line connecting the 6th- and 7th-magnitude stars SAO 134036 and SAO 134041.

The logical place to start for the next group of objects is with the 10th-magnitude open star cluster NGC 2311. Just east of it you should spy a pleasing chain of five 7th- to 9th-magnitude stars that arc southeastward and will lead you to 9th-magnitude SAO 134002 surrounded by the diffuse

▲ PRETTY PATCHES A 10th-magnitude star illuminates the reflection nebula NGC 2170, which also goes by vdB 67. Several bright stars bracket this group of nebulae, making this region easy to find. Look for HD 41335 on the western side and HD 42690 on the eastern side. Pleasing splotches of bright nebulosity dot the region. With a large enough scope, you might snag the Herbig-Haro objects that round out the western side.

nebula **Sh 2-287**. The dark cloud **LDN 1650** fills the area (Dobashi 1534, 1535, and 1536 are part of LDN 1650). Look for the Herbig-Haro object **HH 227** just shy of $2'$ north of SAO 134002. I enjoyed observing them with my 12-inch Dob. Again, a UHC filter may help with Sh 2-287 and HH 227.

French astronomer Stéphane Javelle discovered **IC 466** in 1893. You'll find this isolated, round emission nebula just $24'$ west-southwest of 5th-magnitude 20 Monocerotis. A triangle of 10th-, 11th-, and 12th-magnitude stars frames the nebula nicely. Low-power eyepieces will readily reveal IC 466, but higher magnification will add detail. I see hints of shadowy lanes that indicate that dark nebulae may overlie the bright portions, but none are documented in this area.

The Seagull Nebula and Friends

Our final collection of bright nebulae in Monoceros is cen-



tered on the fantastic emission nebula **IC 2177** (also known as Sh 2-296). Welsh amateur astronomer Isaac Roberts discovered it photographically in 1898. You'll find it on the border with Canis Major, about 3° northeast of the Great Dog's nose, 4th-magnitude Theta (θ) Canis Majoris. I paired an O III filter with my 12-inch Dob and 32-mm Orion Q70 wide-angle eyepiece to observe this target. For smaller telescopes under a dark sky, I recommend using wide-field eyepieces and sweeping the telescope back and forth across the field in order to tease out the bright nebulae from the dark sky on either side.

Let's start on the western side of this large target by popping into Canis Major. About 2° northeast of Theta Canis Majoris, you'll find **vdB 88**, a large nebulosity around the 7th-magnitude central star GU Canis Majoris. Now scan around $\frac{1}{2}^{\circ}$ almost due east for the reflection nebula **NGC 2327**. The nebula has a double star comprising 9th- and 12th-magnitude components separated by about 7" and an attractive arc of 10th-magnitude stars extending about 4' to the northeast. Continuing on a bit more than 1° northeast to **Sh 2-292**, a fascinating and complex object displaying brighter and darker areas centered on the 7th-magnitude blue variable star V750 Monocerotis. I recommend a hydrogen-beta filter and a large telescope to fully enjoy this target. Fan-shaped **vdB 90** (also cataloged as Parsamian Petrosian 70) is perhaps one of the stranger objects on this tour — you'll find it immediately east of 8th-magnitude FZ Canis Majoris. Look for **vdB 92** a bit more than 3' southeast of 9th-magnitude Z Canis Majoris. And finally, the northern section of IC 2177 is

▲ **FAN-SHAPE IN SPACE** NGC 2313 (also known as Parsamian Petrosian 18) comprises the star V565 Monocerotis that illuminates the cloud of gas and dust visible to its east, with a darker cloud obscuring the western side of the nebulosity. This combination generates the fan shape. Astronomers used to refer to objects such as these as *cometary nebulae* due to their distinctive shapes, although that term is now obsolete. Look for this target $9\frac{1}{4}^{\circ}$ west-northwest of 9th-magnitude SAO 133980, the brighter star at bottom left.

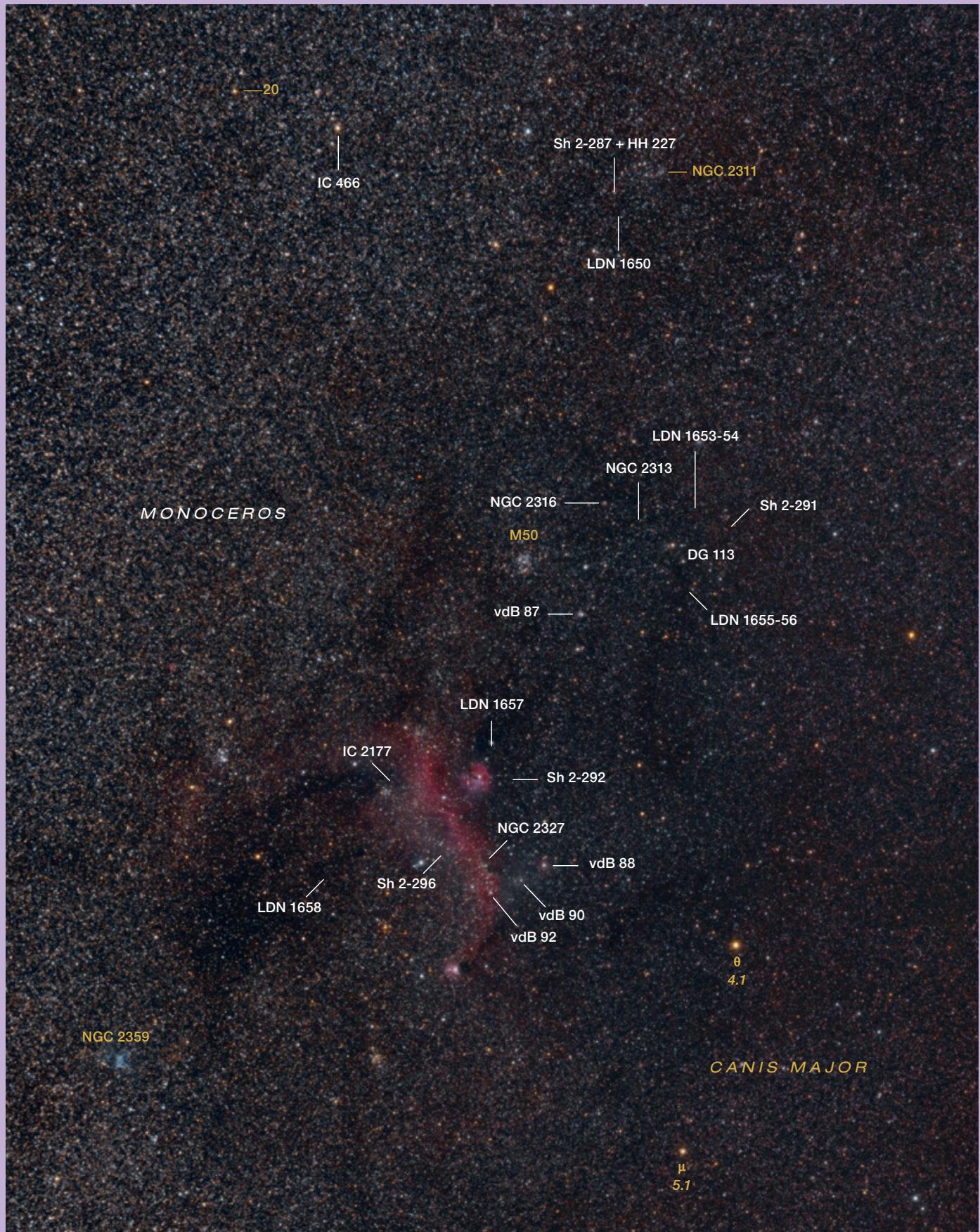
► **CELESTIAL SEAGULL** Straddling the border between Monoceros and Canis Major, the area around IC 2177 is rich with both bright and dark nebulae. Use the image at right to guide your observing session.

involved with **LDN 1657** and **LDN 1658**.

Between the two easier regions of NGC 2170 in the west and IC 2177 in the east we've come across an eclectic collection of objects offering different levels of difficulty. My advice: Get out there and observe with whatever instrument you may have at hand.

■ **RICHARD P. WILDS** first viewed southern Monoceros in the 1960s with a 2-inch Tasco, but it took many more years and different scopes to fully appreciate the region.

FURTHER READING: To learn more about Dobashi dark nebulae and for links to the catalogs, head to https://is.gd/DobashiK_2005 and https://is.gd/DobashiK_2013. Go to Steve Gottlieb's page https://is.gd/astronomy_mall to read all about NGC and IC objects. The table of data for the observing targets discussed here is at https://is.gd/monoceros_nebulae.





Earth

◀ Tidal currents in the Sea of Okhotsk (lower right) transition from smooth to turbulent flows in this natural-color image from the Landsat 8 satellite.

h's Wellspring

We live on a planet covered in water, but where did this water come from?

On December 6, 2020, dozens of scientists and technicians from the Japanese space agency, JAXA, roamed the Australian outback, waiting for a sign from the heavens. They were looking for a bright streak of light that would cross the sky, bringing with it new knowledge about the origins of our solar system. It arrived just before dawn, accompanied by a radio signal that revealed the location of the treasure left behind: a capsule filled with about 5 grams of the near-Earth asteroid 162173 Ryugu, recovered by the Hayabusa 2 robotic spacecraft more than one year earlier and dropped as the craft whizzed by Earth.

Ryugu itself might only be 9 million years old, but it's made of debris from a much older asteroid, a rocky remnant from just after the solar system's formation about 4.6 billion years ago. Asteroids and their icy cousins, the comets, act as time capsules, preserving chemical details that can help us understand how the planets came to be the way they are (*S&T*: May 2020, p. 14). One of those details is where our planet's water comes from.

Scientists have debated the origin of Earth's water for decades. While some think that water was embedded in Earth's original building blocks, many more think it came from elsewhere — for instance, from comets and asteroids that collided with the young Earth when the solar system was in its infancy. Others think the Sun itself might have played a role. So far, none of these ideas can provide an unequivocal answer.

The quest for water's origin is not just about hydrogen and oxygen. It's part of the larger mystery of how Earth got its volatile elements, from the nitrogen that makes up 78% of our atmosphere to the carbon that dominates life's chemistry. The same mechanism most likely furnished Earth with all of these elements, the very things that make our blue planet what it is.

0.2%
Fraction
of Earth's
mass that
is water

Foreign Water

Based on its ocean-covered surface, Earth looks like a planet overflowing with water. Even more hides below the crust: The planet may hold enough hydrogen and oxygen bound in its minerals to fill its oceans a half dozen times or more (estimates vary wildly). But as a whole, Earth is 99.8% rock.

The neighboring planets are equally dry. While Venus and Mars might have had some liquid water on their surfaces at some point in the past, overall they were never much more hydrated than Earth is.

This water paucity is due to how the terrestrial planets were forged. The solar system formed when a giant cloud of gas and dust collapsed to give birth to the Sun. What was left of the cloud, known as the solar nebula, flattened into a disk where the planets coalesced (S&T: May 2020, p. 34). The solar nebula had plenty of hydrogen and oxygen, which are the first and third most abundant elements in the universe, respectively. But close to the young Sun, in the zone where the terrestrial planets formed, temperatures were in the range of 2000K (3000°F), too hot for hydrogen and oxygen to condense and become trapped in rocks. This means that the building blocks of the inner planets remained dry.

Nevertheless, Earth does have water. This water carries a distinctive chemical signature hidden among its hydrogen atoms — the isotope deuterium.

Hydrogen is the simplest atom in the universe, with just one proton and one neutron. Deuterium crams a neutron in with the proton and thus is twice as heavy, even if chemically it behaves like regular hydrogen. Deuterium is also rare: Only 25 out of every million hydrogen atoms in the universe are deuterium, nearly the same ratio found in the Sun and the long-gone solar nebula.

But by the 1980s, scientists had realized that Earth's oceans have seven times more deuterium than the Sun. The discrepancy suggested that Earth obtained much or all of its water from something other than the material its bulk formed from.



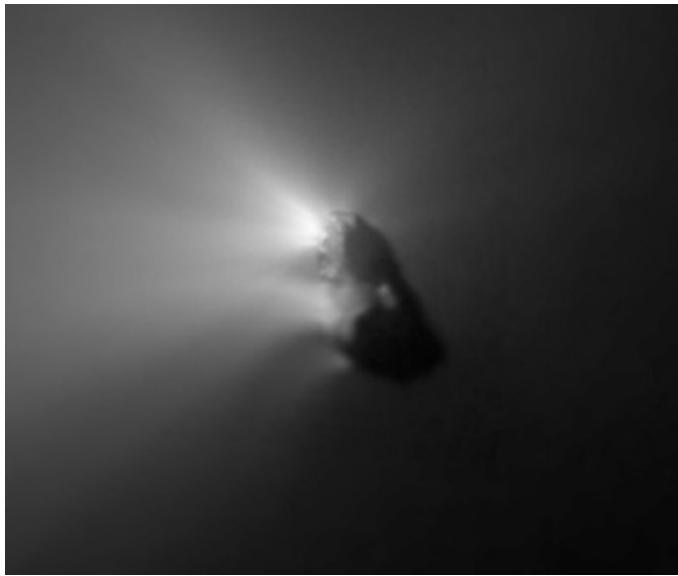
THAT'S NO METEOR Hayabusa 2's return capsule, carrying its precious cargo, streaks through the nighttime sky near Coober Pedy, Australia.

The handiest source to provide this water is the outer solar system, which is rich in water and volatiles and also full of deuterium. Computer simulations of the conditions in the early solar system show that the deuterium-to-hydrogen (D/H) ratio should increase with distance from the Sun, as cold temperatures favor deuterium buildups. This is why many researchers were excited when the European spacecraft Giotto approached Comet Halley in 1986 and found that its deuterium levels might match Earth's — although technical limitations left ample room for error.

Scientists came up with an apparently sound theory: Comets from the outer solar system delivered water to the inner solar system after the planets formed, crashing into the rocky



▲ PRECIOUS CARGO The sample cache from Ryugu descended by parachute to the Australian Outback (left) and broadcast its position with a radio beacon. A helicopter team deployed and found the site soon after, carefully retrieving the wok-size cargo and bringing it home for researchers to pore over in laboratories.



▲ **COMET HALLEY** ESA's Giotto spacecraft took this image of Comet Halley in 1986. Initial measurements indicated that the comet might have a deuterium-to-hydrogen ratio similar to or greater than Earth's, but subsequent analyses pushed the value higher.

planets. This scenario explained at once how Earth came by its water and why it is deuterium-rich.

If only it were that simple.

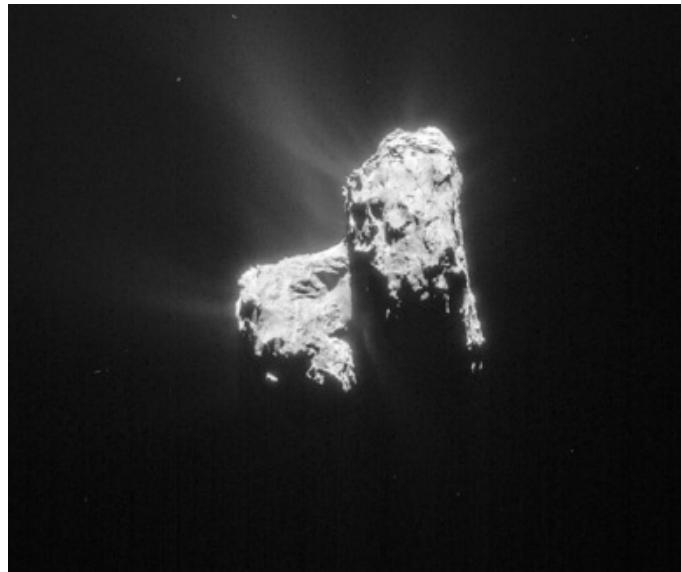
Just a Dash of Comets

Halley proved to be a false lead. Other, Earth-based observations showed that many comets have much higher D/H ratios than Earth's oceans, dampening the prospect that they delivered most of our planet's water. Reanalysis of Giotto's data showed the same thing for Halley. Detailed observations by the European Rosetta spacecraft, which reached Comet 67P/Churyumov-Gerasimenko in August 2014, also revealed that 67P's nucleus was loaded with deuterium, with a D/H ratio more than three times higher than Earth's oceans.

Many processes can increase D/H ratios over time. Radiation and chemical reactions can result in regular hydrogen being lost, while heavier deuterium tends to stay put. But once the ratio has increased, it's unlikely to go back down. This means that if comets delivered Earth's water, then our oceans' D/H value should be much higher.

Rosetta provided another stumbling block to the "comet veneer" scenario. In May 2016, the orbiter made a close approach to 67P to measure the gases emanating from its ice. For three weeks, it circled the comet at a distance of 10 kilometers, sniffing out the composition of the gas with its instruments. The maneuver made flight engineers uneasy as the spacecraft dipped into the cloud of dust and gas surrounding the comet.

Bernard Marty (University of Lorraine, France) and his team used the maneuver to study noble gases, which are easily trapped in the frigid cometary ice. Noble gases are chemi-



▲ **COMET 67P** Material shed by Comet Churyumov-Gerasimenko during its trip past the Sun doesn't match the isotopic levels in Earth's water, suggesting comets have contributed little to our planet's overall composition.

cally inert and don't form compounds or react with other substances, making them perfect tracers of volatiles' origins. Rosetta's measurements were precise enough to pick out a deficit in two of the heaviest isotopes of xenon: xenon-134 and xenon-136. The same feature was found in our atmosphere decades ago, without a feasible explanation.

The researchers concluded that this chemical anomaly on Earth is the fingerprint of terrestrial contamination by comets. They also found the same depletion for the heavy isotopes of krypton, another noble gas, supporting their conclusions. By extrapolating their findings, they estimated that about a quarter of the noble gases in our planet's atmosphere must come from comets.

But that doesn't mean one-quarter of Earth's water comes from comets, too. "Comets are very rich in noble gases," says Marty. "If you add a dash of comets, you will impact the noble gas budget but not the water and nitrogen." The team quantified how much water comets could have contributed to Earth: less than 1%.

Splitting the Waters

If comets weren't the main source of our world's water, maybe asteroids were.

There are two distinct reservoirs of asteroids in the solar system. These reservoirs' compositions were determined by their distance from the Sun when they formed, and were likely enhanced by the rapid growth of Jupiter.

Like Earth, the asteroids that formed close to the Sun could not incorporate much water. But beyond the snow line — the boundary where the temperature was low enough for water to condense into ice — frozen water could readily mix

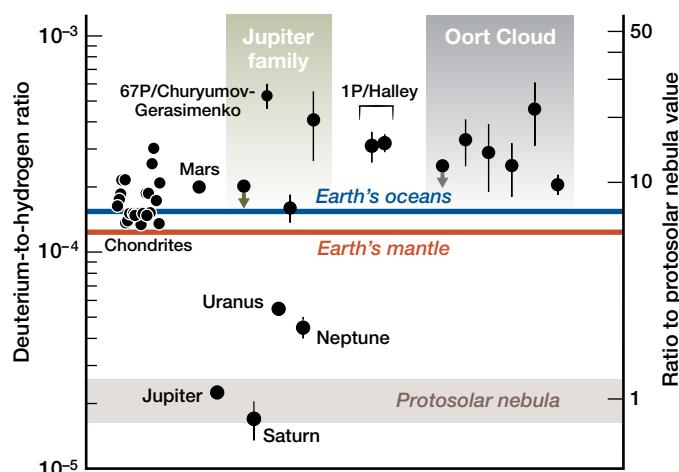
Previously, enstatite chondrites were considered too dry to have contributed a significant amount of water to Earth. That has changed very recently.

with the rocky bits that would eventually merge to form the outer solar system bodies, producing planets, asteroids, and comets teeming with water and other volatiles.

Eventually, the inner regions also cooled down, but water from the outer solar system could not reach them. Once Jupiter reached 20 times the current mass of Earth, its gravitational pull was strong enough that it sucked gas directly from the protoplanetary disk, clearing a gap in it.

“It’s like opening the Red Sea in the Bible,” says Alessandro Morbidelli (Côte d’Azur Observatory, France). The gap prevented dust and pebbles laden with water ice in the outer solar system from drifting into the inner solar system, leaving it dry. This division led to the formation of two separate reservoirs of material in the solar system that, over time, became chemically distinct. Each reservoir developed its own chemical markers, and when we find these markers in a meteorite, asteroid, or comet, we can tell where that object formed. D/H ratios are one marker, but the ratios of other elements’ isotopes are also useful, such as nitrogen-14 to nitrogen-15 or comparisons of oxygen’s three isotopes (oxygen-16, oxygen-17, and oxygen-18).

Meteorites — the charred remains of asteroids that fall to Earth — still carry these isotopic signatures, offering scientists a way of determining their parent bodies’ origins. Scientists classify meteorites based on several characteristics, including their composition and isotopic properties. Chon-



▲ D/H RATIOS ACROSS THE SOLAR SYSTEM Measurements of the ratio of deuterium to hydrogen for different bodies show a wide range of values. Comets — once widely thought to have delivered Earth’s water after our planet’s formation — are generally a poor match for the terrestrial D/H value. (Vertical lines are uncertainty ranges, arrows upper limits.)

drites, for example, are a primitive type of stony meteorite thought to contain some of the most pristine material in the solar system. They formed after the accretion of several types of dust and small grains. Carbonaceous chondrites are part of this group, and they contain lots of water.

Carbonaceous chondrites are hard to come by on Earth, representing only about 3% of all meteorites found. But around three-quarters of all known asteroids — including Ryugu — are dark C-types whose composition and spectra match those of carbonaceous chondrites. A quick glance at the spongy samples recovered by Hayabusa 2 reveals why these meteorites are rare: Carbonaceous chondrites are too fragile to survive on Earth. They either burn up completely in the atmosphere or are quickly weathered on the surface.

Water can make up to about 20% of the mass of CI and CM chondrites, two subgroups of carbonaceous chondrites. This water has a chemical and isotopic composition similar to Earth’s oceans, albeit with a slightly higher D/H ratio — in fact, CI and CM chondrites are the only meteorites that come close to satisfying the full range of chemical constraints for Earth’s volatiles, says Conel Alexander (Carnegie Institution for Science), an expert in primitive meteorites. Cosmochemists estimate that up to 1 or 2% of Earth’s total mass could have been accreted from carbonaceous chondrites without creating conflicts with other isotopes. Since carbonaceous chondrites are so rich in water and other volatiles, that small percentage could have contributed most of the volatiles on Earth, Alexander says.

“And the CI chondrites are what Ryugu seems to be made from,” he adds.

The first analyses of Hayabusa 2’s samples, however, haven’t thrown any conclusive light on the origin of Earth’s water. On one hand, Ryugu’s D/H ratio is about 20% above that of water trapped in Earth’s rocks. On the other hand, Ryugu is drier than CI meteorites. This could mean that Ryugu dried up during its long life in space, maybe due to a close approach to the Sun a few million years ago, or that our collection of meteorites has been polluted by Earth’s water.

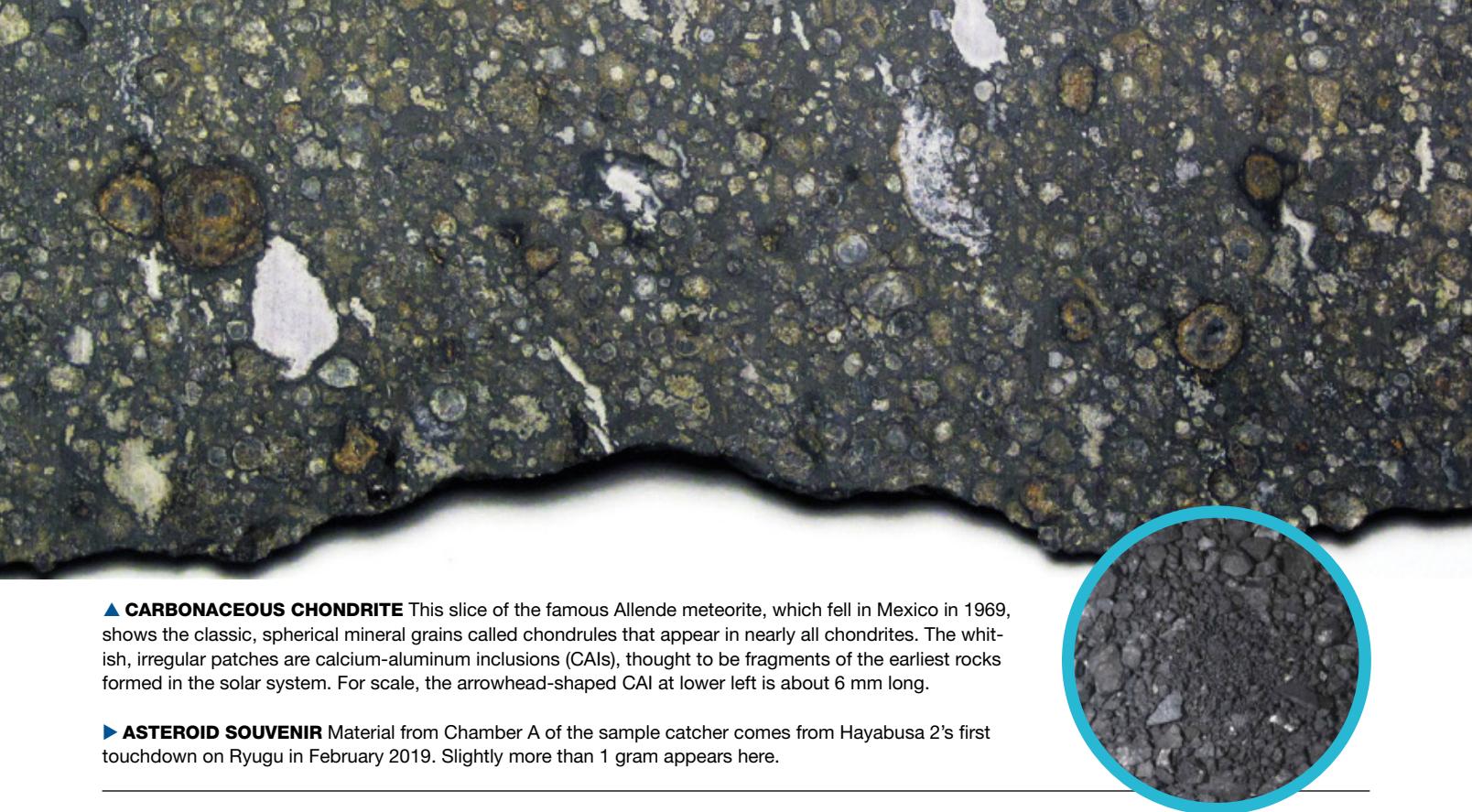
“Has it really changed our picture? Probably not,” Alexander says. “But before I say it’s not really changed anything, I would give it another five years of really detailed study.”

The Not-So-Dry Earth

While carbonaceous chondrites are great candidates for delivering water to our planet, there’s a simpler explanation that has been gaining traction in recent years: Earth’s building blocks maybe weren’t so dry, after all.

Enstatite chondrites are a rare type of meteorite that contain oxygen, titanium, calcium, and molybdenum, with isotopic ratios so close to those of our world that some regard them as either the leftovers from Earth’s creation or at least a very close relative.

Previously, enstatite chondrites were considered too dry to have contributed a significant amount of water to Earth. That has changed very recently. Using new analytical tech-



▲ **CARBONACEOUS CHONDRITE** This slice of the famous Allende meteorite, which fell in Mexico in 1969, shows the classic, spherical mineral grains called chondrules that appear in nearly all chondrites. The whitish, irregular patches are calcium-aluminum inclusions (CAIs), thought to be fragments of the earliest rocks formed in the solar system. For scale, the arrowhead-shaped CAI at lower left is about 6 mm long.

► **ASTEROID SOUVENIR** Material from Chamber A of the sample catcher comes from Hayabusa 2's first touchdown on Ryugu in February 2019. Slightly more than 1 gram appears here.

niques that can measure the composition of tiny mineral grains embedded within meteorites, researchers have found that, trapped in the minerals inside enstatite chondrites, there's enough hydrogen to yield some 3 to 23 oceans' worth of water to Earth during its formation. If Earth was entirely made of this material, it would eliminate the need for a delivery system from the outer solar system.

There is one caveat: Enstatite chondrites' D/H ratio is lower than that of Earth's oceans.

That could be a good thing, though. Recently, a group of researchers led by Karen Meech (University of Hawai'i, Mānoa) found evidence supporting the idea that the ocean's D/H ratio today might not be the same as the primordial water that Earth originally acquired. Instead, reservoirs of primordial water that are trapped deep in the mantle could be a better match.

Oceans have gone through a lot during their history: Volcanism, subduction, the escape of lighter isotopes from the atmosphere, biological activity, giant impacts like the one that formed the Moon . . . all of these can change the D/H ratios over time. "How could the Earth's oceans possibly represent the primordial water?" Meech wondered. "It just didn't make sense."

Geologists have long known that mantle plumes that fuel hot-spot volcanism in places like Hawai'i or Greenland emerge from deep reservoirs, located near the core-mantle boundary. These plumes can bring to the surface material that might have been buried since the early days of the planet's formation. They carry a distinct isotopic signature in their helium atoms: a lack of helium-4, which forms from the radioactive decay of certain elements.

Meech realized that no one had measured the D/H ratios of these rocks, because the technology to do so was new. Along with Lydia Hallis (now University of Glasgow, UK) and several collaborators, she measured the D/H ratios from volcanic rocks with a deep origin from Baffin and Padloping islands in northeastern Canada. These samples revealed D/H ratios up to 25% lower than ocean values.

The finding shows that at least some rocks inside Earth preserve a lower D/H ratio that is closer to the solar nebula values and that could be compatible with an Earth built from enstatite chondrites or a similar material. While the result does not preclude the delivery of a late veneer, it might change our estimations of the contribution comets and asteroids made to the total water budget.

It could also mean that wet planets around other stars could be more common than previously thought. If the building blocks of planets that form close to their stars can preserve enough water to form oceans, then a planetary system's subsequent evolution might play a minor role in the final outcome. It could be that building an Earth-like world doesn't require the complex convergence of events we've experienced in our solar system.

Back to the Skies

In 2010, after a trip full of technical difficulties, the first Hayabusa spacecraft recovered a few grains of asteroid Itokawa and brought them back to Earth. Several teams around the world were allocated bits of this material to analyze, among them Luke Daly (University of Glasgow) and colleagues. In 2021, the team made a surprising find.

All airless surfaces exposed to space change physically and

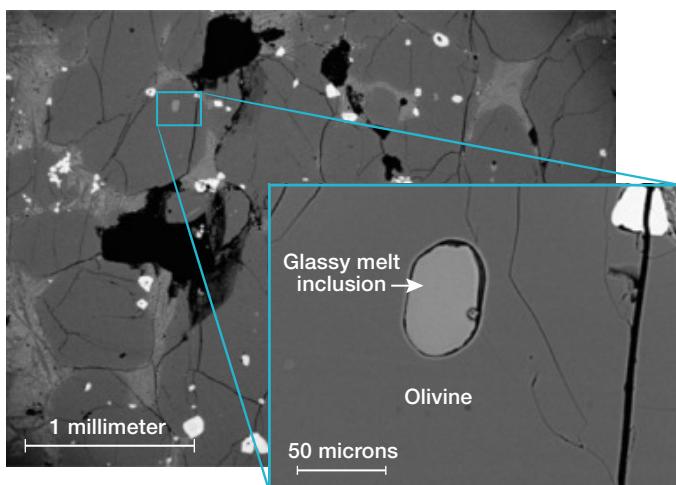
chemically over time, after being subjected to radiation, the solar wind, and micrometeorite impacts. While looking for signs of this space weathering, Daly and his colleagues unexpectedly found that their Itokawa grain was covered by a thin layer of hydroxide molecules (molecules with just one oxygen and one hydrogen atom, OH) and water.

After conducting several experiments, the team concluded that the wet layer was created by the solar wind. The solar wind is a stream of particles (mostly electrons and hydrogen ions, which are just protons) spewed by the Sun. When these protons hit the asteroid's surface, they reacted with the minerals there and stole oxygen atoms to produce hydroxide and water, a theory Daly's team tested successfully in the lab.

"Basically, the formula is one of my favorite simple formulas in planetary science: Proton plus rock equals water," Daly jokes.

Judging by how much water they found in their Itokawa grain, the researchers estimated that a cubic meter of asteroid regolith could contain up to 20 liters of water just from the solar wind. Such regolith wouldn't have to reach Earth by big asteroid impacts: Space dust litters the solar system, and approximately 5,000 metric tons fall to Earth's surface as micrometeorites each year. That means that over eons, a massive amount of Sun-made water has been coming to Earth.

This water is virtually deuterium free, but it wouldn't have been the only water arriving from space. Considering that water-rich asteroids, including carbonaceous chondrites, have on average D/H ratios that are above Earth's ocean value, the team has estimated that a 50:50 mix of water-rich dust and asteroids would yield an excellent match for the isotopic composition of Earth's oceans. "So basically, half a glass of sun-



▲ **MANTLE WATER** This scanning electron microscope image of a basaltic rock from Baffin Island shows the mineral olivine (dark gray grains), which hosts glassy melt inclusions. These inclusions contain tiny amounts of water from Earth's deep mantle.



◀ **EARTH'S BUILDING BLOCKS** Falling in France in 1914, the Saint-Sauveur meteorite is an enstatite chondrite, a type of meteorite with a composition very similar to Earth's. It's possible that such meteorites are leftovers from the material that formed our planet.

shine in every glass of water should explain Earth's ocean composition," Daly says.

Multiple Origins

Many other researchers are also realizing that, rather than a unique reservoir, multiple sources contributed to Earth's volatiles.

"It's such a complicated process, that if you say 'this is the only solution,' then that's a little bit too narrow," Meech says. "I would be very surprised if we didn't have several components that delivered Earth's water."

One likely combination would start with an Earth mostly built by enstatite chondrites, or a similarly dry chondritic material. This material would have provided up to 95% of Earth's mass but only contributed about half of its water. The remaining 4% or 5% would come from carbonaceous chondrites, mostly CI and CMs, that brought with them 50% of the water and up to 80% of the noble gases. Then, about 1% of the water and nitrogen came from comets. These also added up to 20% of noble gases but only about 0.001% of the planet's total mass.

"This is really what comes out from geochemical and cosmochemical analysis, and I think there is no way around it: The data speak, and it's very, very, very consistent," Morbidelli says. "I think it makes a lot of sense that the Earth accretes most of its mass from local, non-carbonaceous material."

Both Morbidelli and Meech argue for more exploration to find pristine water reservoirs in the solar system, especially those that we still might not have sampled yet. Meech is spearheading a mission proposal called Proteus, to explore a class of comet-like objects found in the asteroid belt. Known as *main-belt comets*, these bodies emit water and dust every time their orbits approach the Sun, similar to the way comets behave. Their orbits indicate they've been there since the early days of the solar system and might be part of the collection of wet objects that were thrown around by the giant planets early on: While their brethren delivered volatiles to Earth, they got stuck in the asteroid belt.

It's very likely that many, still-unknown types of material helped form Earth but aren't represented in the meteorite collections, Morbidelli says. "The book of solar system formation is written in the data, and when we have enough data, we will simply read what happened," he says. Even if the book is missing some pages, lost forever in the chaotic process that resulted in our unique planetary system, "there is a story and this story is unique, so we can unveil it completely."

■ **JAVIER BARBUZANO** is a freelance science journalist based in Barcelona, Spain.



OBSERVING

March 2023

1 DUSK: Look toward the west after sunset to catch the brilliant sight of Venus and Jupiter a mere $1/2^\circ$ apart. Follow the pair in deepening twilight as they sink toward the horizon. Turn to page 46 for more on this and other events listed here.

2 EVENING: High in the southeast, the waxing gibbous Moon is around $1\frac{1}{2}^\circ$ from Gemini's brightest star, Pollux.

5 EVENING: The slightly fatter Moon is in Leo, the Lion, 4° or less left of Regulus.

5 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:47 p.m. PST (see page 50).

8 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:36 p.m. EST.

9 DUSK: The waning gibbous Moon and Spica rise together in the east-southeast, around 5° between them. Watch as the pair climb higher during the night, while at the same time getting closer. By dawn, a bit more than 2° separates them.

12 DAYLIGHT-SAVING TIME starts at 2 a.m. for most of the U.S. and Canada.

14 MORNING: Look toward the southeast to see the last-quarter Moon and Antares, the Scorpion's smoldering heart, rise in tandem. The Moon trails the red supergiant by a bit more than 4° .

20 SPRING BEGINS IN THE NORTHERN HEMISPHERE at the equinox, 5:24 p.m. EDT (2:24 p.m. PDT).

22 DUSK: Low above the western horizon a razor-thin Moon, just one day past new, is $1\frac{1}{2}^\circ$ upper left of Jupiter. Catch this sight before it sinks out of view. Venus blazes above the pair.

23, 24 DUSK: The lunar crescent has grown slightly while climbing in the west where it visits Venus. The first evening, the Moon is poised some 5° below the planet, then hopscotches over it to hang some 6° above it the following evening.

25 DUSK: High in the west, the waxing crescent Moon is in Taurus, about $1\frac{1}{2}^\circ$ left of the Pleiades.

27 DUSK: Right after sunset look toward the west to see a string of celestial bodies. They stretch from the Moon, one day before first quarter, gleaming in Taurus with Mars upper left and Venus farther lower right. Mercury and Jupiter adorn the western horizon, with less than $1\frac{1}{2}^\circ$ between them.

28 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:22 p.m. PDT.

29 DUSK: The Moon has cycled back to Gemini where it's $3\frac{1}{2}^\circ$ below Pollux.

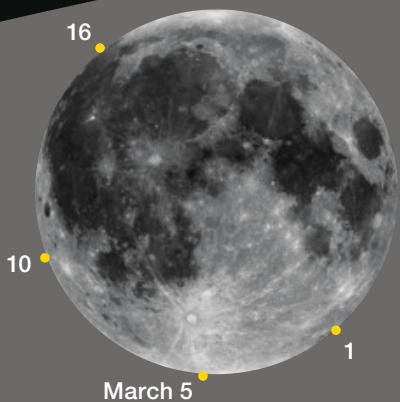
— DIANA HANNIKAINEN

Viewers could witness a very similar sight as seen here on the evening of March 24th — the crescent Moon bathed in earthshine with Venus nearby (although the Moon's phase will be different). Turn to page 22 to read more on earthshine. ALAN DYER

MARCH 2023 OBSERVING

Lunar Almanac

Northern Hemisphere Sky Chart



Yellow dots indicate which part of the Moon's limb is tipped the most toward Earth by libration.
NASA / LRO

MOON PHASES

SUN	MON	TUE	WED	THU	FRI	SAT
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	



FULL MOON

March 7
12:40 UT



LAST QUARTER

March 15
02:08 UT



NEW MOON

March 21
17:23 UT



FIRST QUARTER

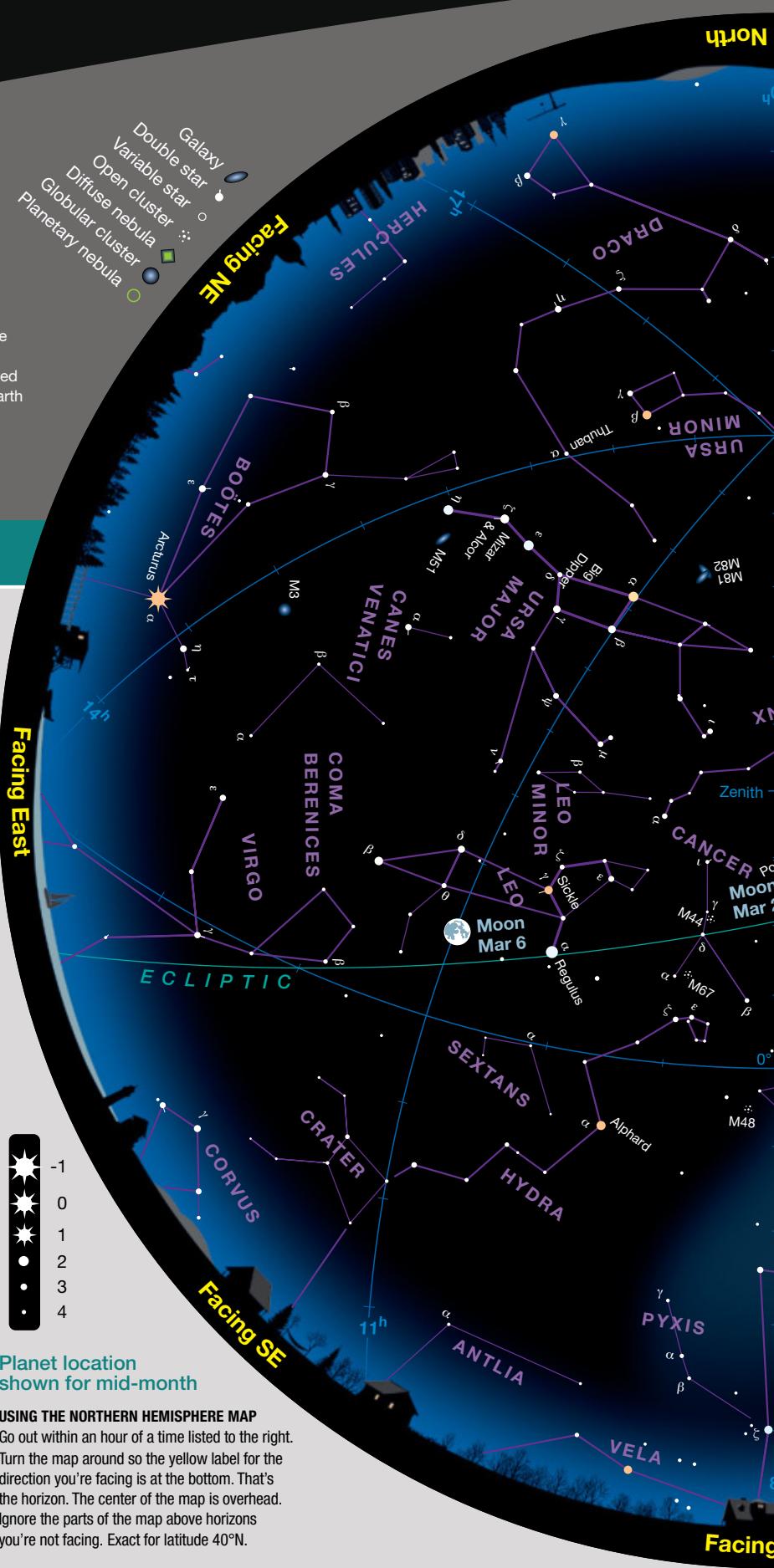
March 29
02:32 UT

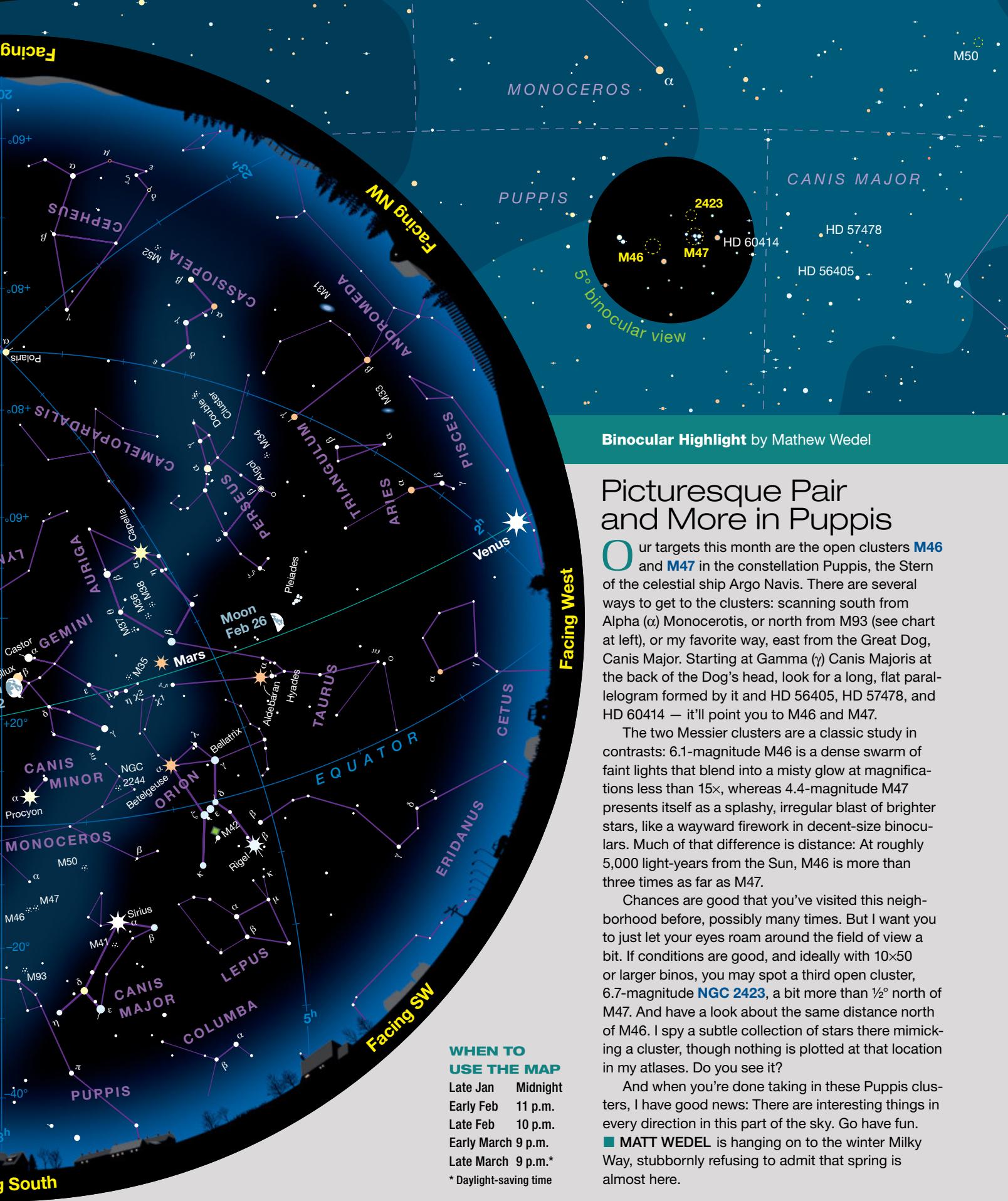
DISTANCES

Apogee	March 3, 18 ^h UT
405,889 km	Diameter 29' 26"
Perigee	March 19, 15 ^h UT
362,697 km	Diameter 32' 57"
Apogee	March 31, 11 ^h UT
404,917 km	Diameter 29' 31"

FAVORABLE LIBRATIONS

- Lyot Crater March 1
- Newton Crater March 5
- Lacus Veris March 10
- Stokes Crater March 16





Mercury



Venus



Mars



Jupiter



Saturn



Uranus



10"

▲ **PLANET DISKS** are presented north up and with celestial west to the right. Blue ticks indicate the pole currently tilted toward Earth.

► ORBITS OF THE PLANETS

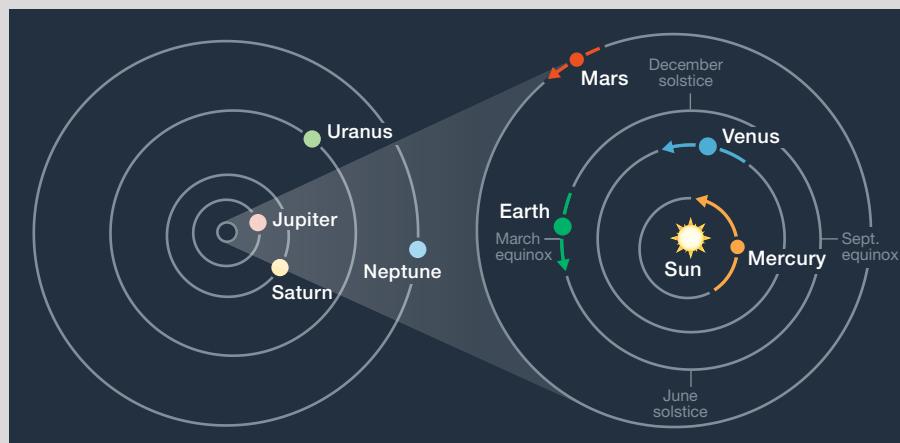
The curved arrows show each planet's movement during March. The outer planets don't change position enough in a month to notice at this scale.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury** visible at dusk starting on the 26th • **Venus** visible at dusk all month • **Mars** transits the meridian at sunset and sets in the predawn • **Jupiter** visible low in the west at dusk until the 30th • **Saturn** visible at dawn starting on the 23rd.

March Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	22 ^h 45.4 ^m	-7° 53'	—	-26.8	32' 17"	—	0.991
	31	0 ^h 35.7 ^m	+3° 51'	—	-26.8	32' 02"	—	0.999
Mercury	1	21 ^h 57.5 ^m	-14° 43'	14° Mo	-0.5	5.0"	93%	1.340
	11	23 ^h 04.0 ^m	-8° 09'	6° Mo	-1.3	4.9"	98%	1.369
	21	0 ^h 13.8 ^m	+0° 23'	4° Ev	-1.8	5.1"	99%	1.328
	31	1 ^h 24.5 ^m	+9° 41'	13° Ev	-1.2	5.7"	83%	1.173
Venus	1	0 ^h 39.0 ^m	+3° 28'	31° Ev	-3.9	12.2"	86%	1.371
	11	1 ^h 23.5 ^m	+8° 34'	33° Ev	-3.9	12.7"	83%	1.318
	21	2 ^h 08.7 ^m	+13° 22'	35° Ev	-4.0	13.2"	81%	1.260
	31	2 ^h 55.1 ^m	+17° 38'	37° Ev	-4.0	13.9"	78%	1.198
Mars	1	5 ^h 10.3 ^m	+25° 22'	99° Ev	+0.4	8.2"	90%	1.144
	16	5 ^h 38.8 ^m	+25° 35'	90° Ev	+0.7	7.2"	90%	1.294
	31	6 ^h 10.5 ^m	+25° 30'	83° Ev	+1.0	6.5"	90%	1.444
Jupiter	1	0 ^h 44.2 ^m	+3° 33'	32° Ev	-2.1	34.2"	100%	5.766
	31	1 ^h 10.1 ^m	+6° 17'	9° Ev	-2.0	33.2"	100%	5.937
Saturn	1	22 ^h 06.0 ^m	-13° 03'	11° Mo	+0.9	15.4"	100%	10.791
	31	22 ^h 19.1 ^m	-11° 54'	37° Mo	+1.0	15.7"	100%	10.587
Uranus	16	2 ^h 53.5 ^m	+16° 14'	51° Ev	+5.8	3.5"	100%	20.270
Neptune	16	23 ^h 42.8 ^m	-3° 08'	1° Ev	+8.0	2.2"	100%	30.905

The table above gives each object's right ascension and declination (equinox 2000.0) at 0^h Universal Time on selected dates, and its elongation from the Sun in the morning (Mo) or evening (Ev) sky. Next are the visual magnitude and equatorial diameter. (Saturn's ring extent is 2.27 times its equatorial diameter.) Last are the percentage of a planet's disk illuminated by the Sun and the distance from Earth in astronomical units. (Based on the mean Earth-Sun distance, 1 a.u. equals 149,597,871 kilometers, or 92,955,807 international miles.) For other timely information about the planets, visit skyandtelescope.org.



Sighting the Beehive

The celestial Crab holds a misty, naked-eye treasure.

This month let's pay a visit to an open star cluster so fascinating that it has earned several vivid nicknames and has even been used to forecast the weather. The cluster is M44 in Cancer, the Crab. It's best known as "the Beehive."

The Beehive nickname comes from the cluster's telescopic appearance: bunches of similarly bright stars (the "bees") gathered into a roughly elliptical, upright form (the "hive"). Sounds intriguing. But M44 is also a very interesting naked-eye object.

First of all, it's big. Under good conditions, M44 appears as a fuzzy patch roughly $1\frac{1}{2}^\circ$ across — three Moon diameters wide. That's wider than the low-power field of many telescopes. Second, it's relatively bright. Of the 88 officially recognized constellations, dim Cancer is the only one whose brightest object is not a star but a star cluster. Nearly 600 light-years distant, M44 shines with a total magnitude of 3.1. That's almost half a magnitude brighter than the constellation's brightest star, 3.5-magnitude Beta (β) Cancri.

Cancer is so dim that it's been dismissively described as "the blank spot between Gemini and Leo." In reality, its main stars and the Beehive can be seen even in fairly light-polluted skies. Of course, we have to remember that an extended object such as M44 spreads its light over a much greater area of sky than a single, pinpoint star does. That means the Beehive is more adversely affected by bright conditions.

In ancient times, the cluster's naked-eye visibility was supposed to predict the coming of stormy weather. If individual stars in the constellation could be seen,



▲ **CRABTASTIC CLUSTER** Naked-eye open cluster M44 lies at the heart of the dim constellation Cancer, the Crab. Use the star map on pages 42 and 43 to identify the constellation's stars and M44 in the photo above.

but not the Beehive, poor weather was expected. This prognostication method isn't as fanciful as it might first seem. After all, a shield of cirrus clouds often precedes a storm system — exactly the kind of thin cloud cover that tends to hide extended objects such as M44 before extinguishing individual stars.

Although I've been referring to the cluster as the Beehive, it wasn't known by that name in ancient times. Back then it was called Praesepe, Latin for manger. This title came about because of a delightful visualization. The little haze of stars is just west of and midway along a 3° north-south line that connects Gamma (γ) and Delta (δ) Cancri — the northern and southern donkeys (*Asellus Borealis* and *Australis*, respectively), who had come to the manger to eat.

Ready for a super observing challenge? The brightest star in M44 is 6.3-magnitude Epsilon (ϵ) Cancri, the star marking the southwest corner of a lopsided square near the cluster's center. In fact, roughly a dozen stars in the Bee-

hive shine at between 6.3 and 6.9. Is it possible to see any of them individually without optics? The feat apparently has been pulled off a few times by observers with truly extraordinary eyes and skies.

One final, remarkable feature of the Beehive is its proximity to the ecliptic, which means solar system objects regularly appear to pass near (or even through) it. Indeed, Mars will traverse the cluster this coming June. But it's not just the Moon and planets that visit. Forty years ago I watched the head of Comet IRAS-Araki-Alcock (C/1983 H1) pass just east of the Beehive with my eyes alone. This was a remarkable comet that passed very close to Earth — the closest one in more than 200 years. To the naked eye, IRAS-Araki-Alcock was a big, bright patch of radiance several times larger and two magnitudes brighter than the Beehive.

■ **FRED SCHAAF** enjoys hearing from readers. He can be e-mailed at fschaaf54@gmail.com.

To find out what's visible in the sky from your location, go to skyandtelescope.org.

Hello Saturn, Goodbye Jupiter

Several bright planets hang near the horizon — one at dawn, three at dusk.

WEDNESDAY, MARCH 1

The month kicks off with a real bang — there's no saving the best for last this time. Look to the west shortly after sunset and you can't help but be dazzled by the two brightest planets side by side with just $\frac{1}{2}^\circ$ between them. The dazzling duo are, of course, **Jupiter** and **Venus**. The reigning Evening Star gleams at magnitude -3.9 , while Big Jove is -2.1 . If you've been keeping an eye on them over the preceding several nights, you'll have noticed Venus climbing higher as Jupiter sinks lower, making this evening's meeting inevitable. But is it especially rare? Perhaps not as rare as you might expect.

The two planets meet with some regularity — usually once each year. But not every conjunction is equally close, and sometimes they occur during daylight hours. Jupiter and Venus had a similarly close encounter at dawn on April 30, 2022, and they next pair up in May 2024, though they'll appear too near the Sun to observe. You'll have to wait until August 2025 to see the planets together again, though on that occasion they'll be twice as far apart as tonight. A conjunction as good as this evening's doesn't come until 2027. In other words, tonight's is a show you don't want to miss.

THURSDAY, MARCH 2

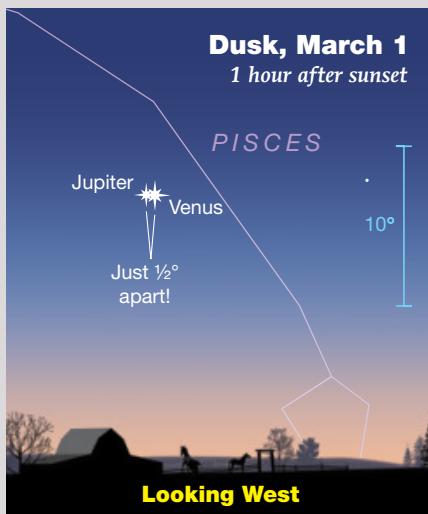
The **Moon**'s closest approach to a bright star this month occurs this evening,

► These scenes are drawn for near the middle of North America (latitude 40° north, longitude 90° west). European observers should move each Moon symbol a quarter of the way toward the one for the previous date; in the Far East, move the Moon halfway.

when a waxing gibbous sits a little more than $1\frac{1}{2}^\circ$ below 1.1-magnitude **Polux**, in Gemini. The gap between them is smallest at around 6:41 p.m. EST. Pollux is Gemini's leading light, but only the fourth-brightest star the Moon passes on its eastward journey along the ecliptic. Tonight's pairing also has a second act after midnight. That's when the Moon is positioned along a line that includes Pollux and fellow stellar Twin, **Castor**. The three-in-a-row configuration occurs at roughly 2 a.m. EST, on the morning of March 3rd. By then, however, the Moon has drifted away from Pollux, and now they're separated by more than $2\frac{1}{2}^\circ$.

SUNDAY, MARCH 19

At dawn today the earthlit, waning crescent **Moon** sits about 5° below right of **Saturn**. This certainly isn't the most visually striking conjunction you're ever going to see, but it's nonetheless noteworthy because it may well be your first glimpse of Saturn at the start of its

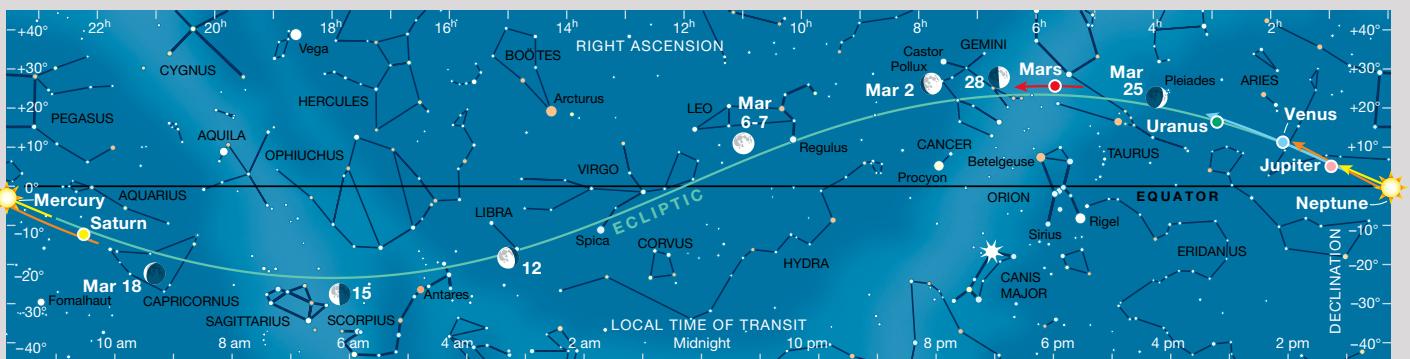


new apparition. The ringed planet was last seen low in the dusk sky early last month, just before its conjunction with the Sun on February 16th. Saturn is still very low as morning twilight claims the sky, so you'll need an unobstructed east-southeastern horizon and (probably) a pair of binoculars to catch it. Even though the Moon is somewhat lower than Saturn, you'll probably spot it first, which means you can use the lunar crescent to guide you to the planet. Don't worry if you can't locate Saturn, though — from this point onwards, it climbs a little higher each morning. You'll get your first look eventually!

WEDNESDAY, MARCH 22

As Saturn reappears at dawn, **Jupiter** slips away at dusk. For naked-eye observers, Jupiter has only another week or so of visibility as it inches sunward,





▲ The Sun and planets are positioned for mid-March; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side illuminated). "Local time of transit" tells when (in Local Mean Time) objects cross the meridian — that is, when they appear due south and at their highest — at mid-month. Transits occur an hour later on the 1st, and an hour earlier at month's end.

destined for its solar conjunction on April 11th. We'll have to wait until early May before the big planet follows Saturn and pops up in the east at dawn. In the meantime, Jupiter has one last hurrah when it receives a visit from the **Moon**. And if you didn't manage to see the Moon's meet-up with Saturn, you'll be pleased to know that this evening's conjunction is quite a bit more favorable.

That's due to two factors. First, at magnitude -2.0 , Jupiter is 13 times brighter than Saturn. Second, Jupiter is positioned more than twice as high in the sky during twilight. Thirty minutes after sunset, it's about 7° above the west horizon. But perhaps most importantly for conjunction-watchers is the fact that

the Moon is only $1\frac{1}{2}^\circ$ away. And what a young, wafer-thin crescent it is! The Moon is only a bit more than 2% illuminated and some 33 hours past new. Be sure to try your binoculars on this sight to catch one of Jupiter's satellites (Callisto, upper left of the Jovian disk), and a splendid display of earthshine on the Moon's "unlit" side (see page 22).

MONDAY, MARCH 27

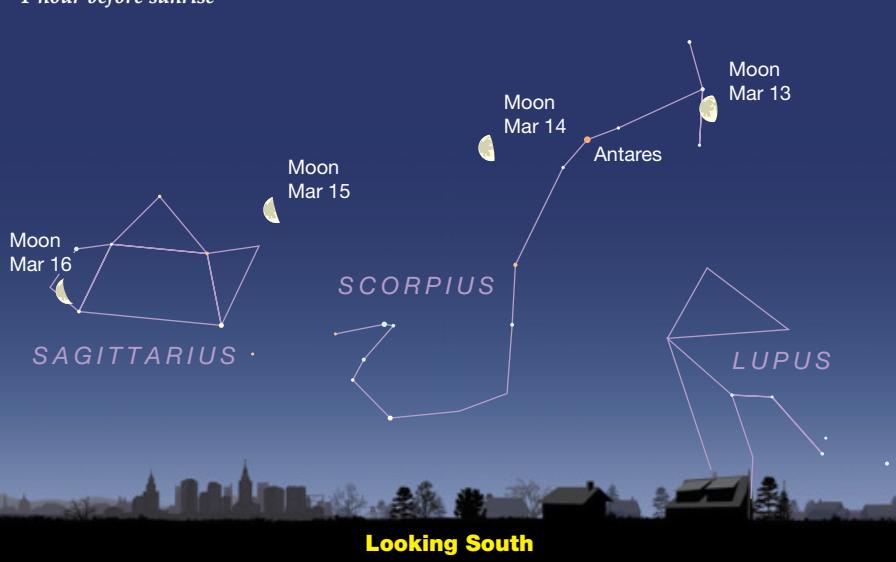
What comes after a "last hurrah"? How about an encore performance. **Jupiter** has one last notable encounter before it exits the evening stage: a meet-up with **Mercury**. The innermost planet shines at magnitude -1.4 and is climbing higher each night as it races toward

its greatest elongation from the Sun, which coincidentally happens on April 11th — the same date as Jupiter's solar conjunction. Like two ships that pass in the night (well, more like bright twilight), they briefly share the same patch of sky, separated by less than $1\frac{1}{2}^\circ$. This won't be any easy pairing to see, however. Half an hour after sunset, the two planets hover just $3\frac{1}{2}^\circ$ above the west-northwest horizon. It's virtually certain you're going to need binoculars (and a very clear sky) to tease them out from dusk's bright glow.

■ Consulting Editor **GARY SERONIK** doesn't mind bidding farewell to Jupiter when it's replaced by Saturn.

Dawn, March 13 – 16

1 hour before sunrise



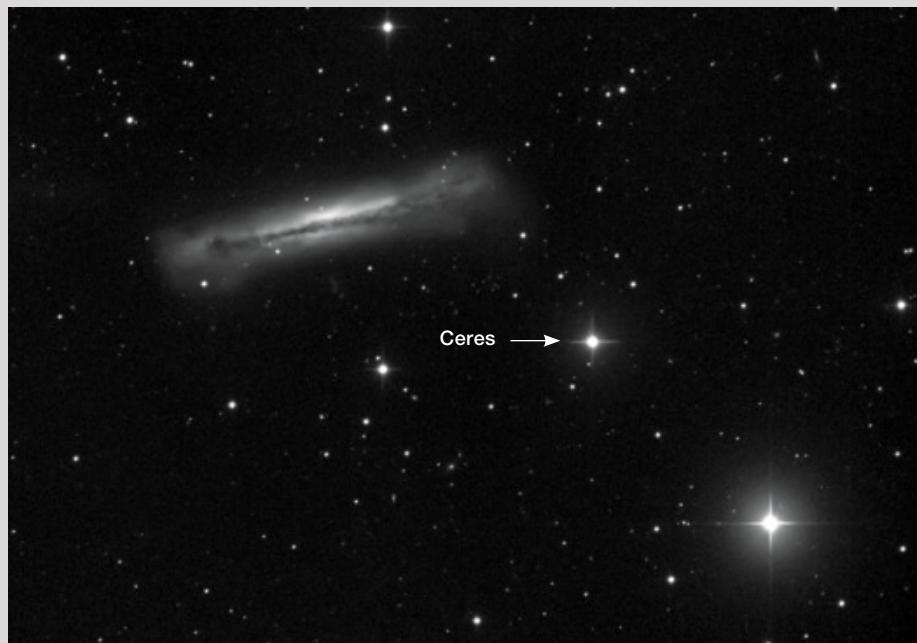
Dusk, March 22 – 24

45 minutes after sunset



Ceres at Opposition

The brightest dwarf planet visits galaxies in Virgo during its upcoming apparition.



Following 1 Ceres is going to be a lot of fun this month. It reaches opposition on March 21st in Coma Berenices at magnitude 6.9 — its brightest apparition in five years. From the very darkest skies, experienced observers might be able to glimpse the tiny world naked eye. On opposition day, Ceres lies 239.5 million kilometers (148.8 million miles) from Earth. It won't be as bright or as close again until 2032.

Most of us will find binoculars necessary for keeping an eye on this dual-citizen dwarf-planet/asteroid as it arcs through the northern half of the Virgo Galaxy Cluster, the richest and brightest such collection in the sky. Along the way, Ceres will have several close encounters with bright cluster members, including M88, M91, and M100. In May, when it resumes direct motion and circles back eastward, it

skirts the cluster's southern border in a slow-motion galactic lasso.

To find Ceres as March begins, start at 2.8-magnitude Epsilon (ϵ) Virginis and slide 5.1° west to 5th-magnitude Rho (ρ) Virginis, which forms a wide optical pair with 6.2-magnitude 27 Virginis. The Rho duo make a handy step-



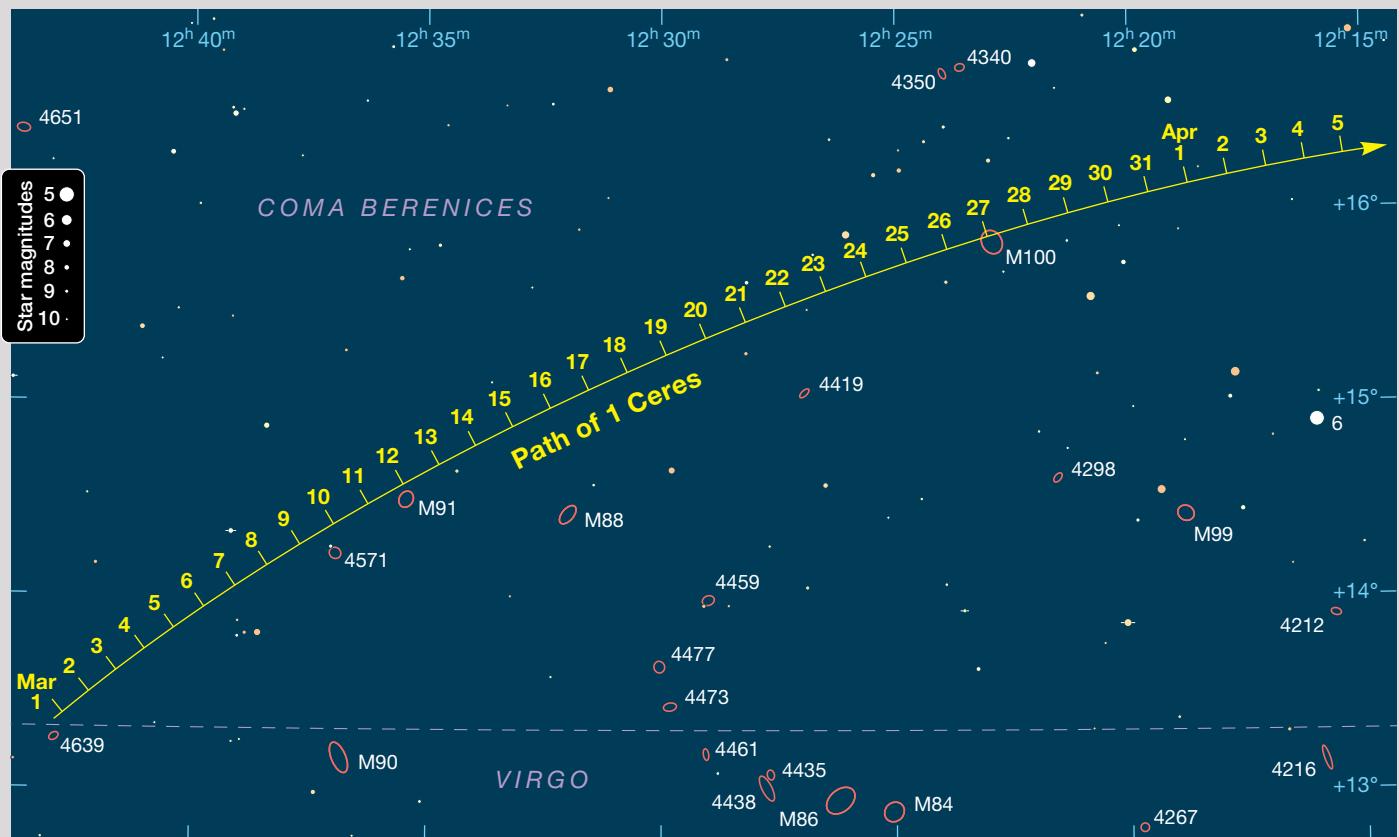
► On November 6, 2022, Ceres skimmed 6' southwest of the Hamburger Galaxy, NGC 3628, in Leo. The solar system's brightest and closest dwarf planet spends much of its current apparition galaxy-hopping in Coma Berenices and Virgo.

pingstone to the asteroid. Ceres is 3.3° north of the pair on the 1st and slowly loops westward in retrograde motion at a rate of around 10' per day, gradually increasing to nearly 13' per day by the end of the month.

All asteroids appear starlike in most telescopes, but given its relative proximity to Earth at the time of opposition it may be possible to resolve Ceres as a minute disk. Consider Europa, the smallest of the Galilean satellites, which spans about 1" when Jupiter is near opposition. The distant moon looks like the tiniest of dots in my 10-inch Dob under high magnification in excellent seeing. Ceres will swell to 0.8" at opposition, presenting a tempting challenge for those who enjoy pushing the limits.

Imagers and visual observers alike will find this month a great opportunity to catch the dwarf planet keeping decidedly colossal company. Ceres has close conjunctions with several prominent galaxies on four different nights: March 11th, 5' north of M91 (mag. 10.2); March 14th, 32' northeast of M88 (mag. 9.6); March 21st, 4' northeast of NGC 4421 (mag. 11.6); and on March 26th, 2.2' north of M100 (mag. 9.4). (Distances noted are from each galaxy's

► NASA's Dawn spacecraft captured this image of Ceres in May 2015 when the probe was just 13,641 km (8,476 mi) above the dwarf planet's surface. The bright spot right of center is the 34-km-wide impact crater Haulani.



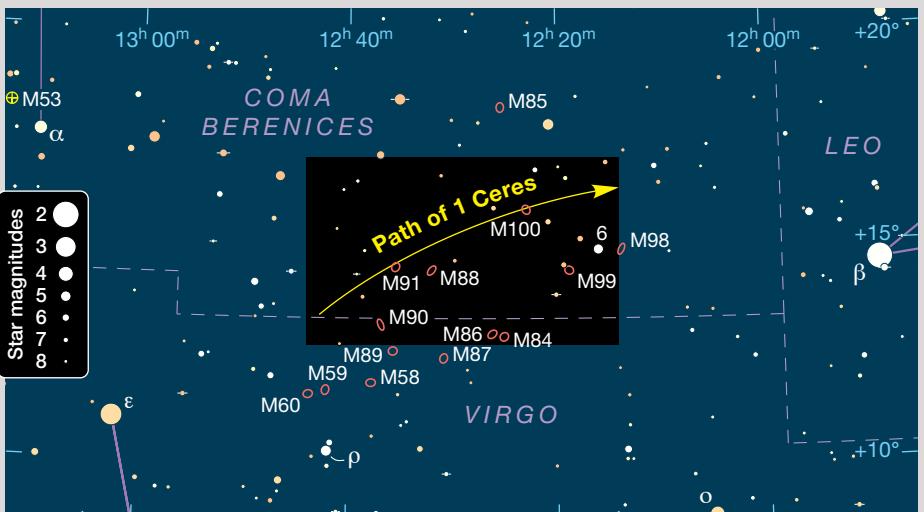
▲ Positions are shown for 0h UT.

center, at roughly 11 p.m. EDT).

The last of these encounters may be the most compelling. Not only is M100 bright, but it's also large, presenting an apparent size of 7.5' by 6.1'. For several hours centered on the time of closest approach (about 10 p.m. EDT), Ceres will hover directly over one of the galaxy's spiral arms, impersonating a wickedly luminous supernova. Transient hunters beware!

NASA's Dawn spacecraft — the first mission to a dwarf planet — arrived at Ceres in 2015 and sent back photos and other data before running out of fuel in October 2018. Although officially pronounced dead on November 1st that year, mission scientists expect the probe to orbit Ceres for at least another 50 years before it spirals downward and crashes onto the dwarf planet's surface.

Dawn revealed that Ceres is rich in water, clay, and organic compounds, and may still harbor remnants of a subsurface ocean. Brilliant white patches in the 92-km-wide crater Occator are



sodium carbonate salt deposits thought to have originated when fissures from a massive meteorite strike allowed briny waters to ooze onto the surface.

Ceres also has a lot of ammonia-rich clay, which is an unusual substance to find on a main-belt object, though it's common in the outer solar system. Its presence is the reason scientists suspect that the dwarf planet originated beyond the orbit of Saturn and

migrated inward. Astronomers also believe Ceres is a protoplanet — a body with sufficient mass and internal heat to have a differentiated interior with a core and mantle. Jupiter's take-no-losers gravitational field stymied its growth and path to planethood.

Dwarf planet, protoplanet, or asteroid — no matter how you choose to categorize it, Ceres awaits your attention this spring.

See Jupiter and Venus in Daylight

I'VE ALWAYS ENJOYED observing planets in daylight hours. Seeing other worlds in a blue sky makes them seem closer somehow — like they're part of an earthly scene. As noted on page 45, on March 1st Venus and Jupiter will pair up just $\frac{1}{2}^\circ$ apart in a dazzling twilight conjunction. By all means, be sure to view this spectacle at dusk, but why not get a sneak peek and view the planetary pair by daylight? Under haze-free skies, Venus is an easy find if you know precisely where to look. Shining at magnitude -3.9 , careful observers can spot it without optical aid even at high noon. But try binoculars to make things easier.

If you choose roughly 3 p.m. local time for your attempt, you can use the waxing gibbous Moon (some 30° above the east-northeastern horizon) to focus your optics. That's absolutely crucial for daytime planet hunting — if you're off even a little bit, the tiny orbs will

melt into the blue sky. Next, position yourself so that when you face the Sun its disk is blocked by a building or trees. Extend your hand to the sky and mark off three fists (about 30°) to the upper left of the Sun. Now use your binoculars to carefully sweep that area of sky to find Venus. With luck you'll spot a pure white spark and the tiny, -2.1 -magnitude disk of Jupiter $\frac{1}{2}^\circ$ to its left.

Finally, lower your binoculars and try to see Venus with your eyes alone. Can you discern Jupiter, too? If not, wait closer to sunset and try again. This time-tested (and admittedly crude) method works well enough, but of course we have much better tools at our disposal. An accurately aligned Go To telescope will make short work of finding the pair. In a scope, Venus presents a waning gibbous disk, while Jupiter will likely display both its dusky equatorial belts.

Minima of Algol

Feb.	UT	Mar.	UT
2	16:44	3	8:58
5	13:33	6	5:47
8	10:23	9	2:36
11	7:12	11	23:26
14	4:02	14	20:15
17	0:51	17	17:04
19	21:40	20	13:54
22	18:30	23	10:43
25	15:19	26	7:32
28	12:08	29	4:22

These geocentric predictions are from the recent heliocentric elements $\text{Min.} = \text{JD } 2457360.307 + 2.867351E$, where E is any integer. They were derived by Roger W. Sinnott from 15 photoelectric series in the AAVSO database acquired during 2015–2020 by Wolfgang Vollmann, Gerard Samolyk, and Ivan Sergey. For a comparison-star chart and more info, see skyandtelescope.org/algol.



▲ Perseus is conveniently placed high in the northeast during evening hours in March. Every 2.7 days, Algol (Beta Persei) dips from its usual magnitude 2.1 to 3.4 and back. Use this chart to estimate its brightness in respect to comparison stars of magnitude 2.1 (Gamma Andromedae) and 3.4 (Alpha Trianguli).

Action at Jupiter

THIS MONTH EFFECTIVELY represents the end of the current Jupiter apparition as the planet loses altitude on its way toward its April 11th solar conjunction. On March 1st, the planet shines at magnitude -2.1 and sets $2\frac{1}{2}$ hours after the Sun. Half an hour after sunset, it hovers some 22° above the horizon — high enough for decent telescopic views. By the end of the month, however, Jupiter sinks below the horizon just 40 minutes after sunset. The big planet will reappear at dawn in early May, as it begins a new apparition.

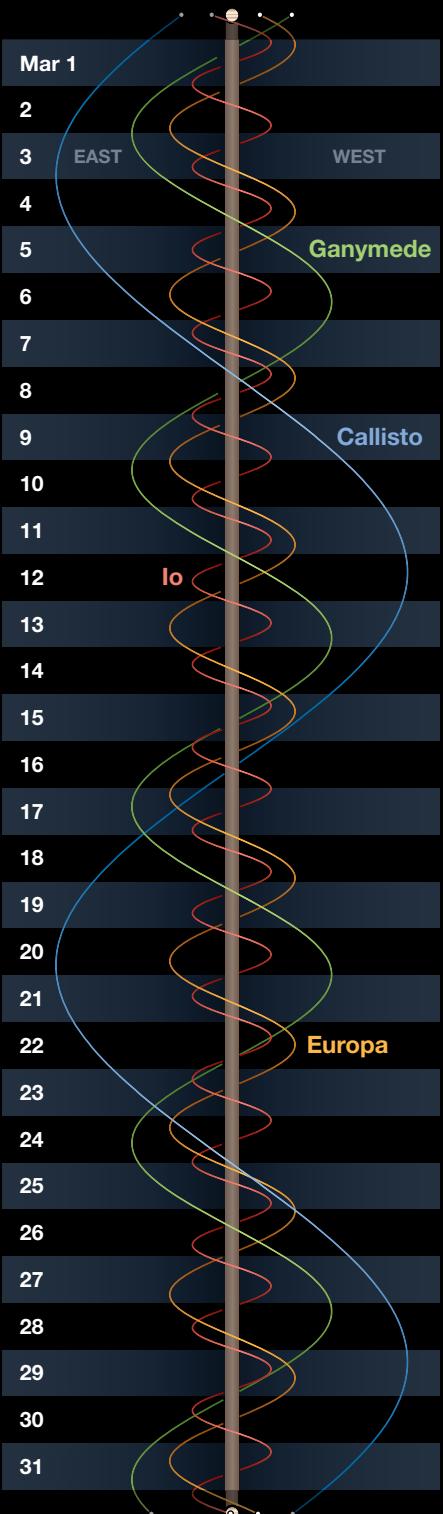
Any telescope reveals the four big Galilean moons, and binoculars usually show at least two or three. The moons orbit Jupiter at different rates, changing positions along an almost straight line from our point of view on Earth. Use the diagram on the facing page to identify them by their relative positions on any given date and time. All the observable interactions between Jupiter and its satellites and their shadows are tabulated on the facing page. Find events timed for when Jupiter is at its highest at dusk.

Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Standard Time is UT minus 5 hours.)

February 1: 1:12, 11:08, 21:04; **2:** 6:59, 16:55; **3:** 2:51, 12:47, 22:43; **4:** 8:39, 18:35; **5:** 4:31, 14:26; **6:** 0:22, 10:18, 20:14; **7:** 6:10, 16:06; **8:** 2:02, 11:57, 21:53; **9:** 7:49, 17:45; **10:** 3:41, 13:37, 23:32; **11:** 9:28, 19:24; **12:** 5:20, 15:16; **13:** 1:12, 11:08, 21:03; **14:** 6:59, 16:55; **15:** 2:51, 12:47, 22:42; **16:** 8:39, 18:34; **17:** 4:30, 14:26; **18:** 0:22, 10:18, 20:13; **19:** 6:10, 16:05; **20:** 2:01, 11:57, 21:53; **21:** 7:49, 17:45; **22:** 3:41, 13:36, 23:32; **23:** 9:28, 19:24; **24:** 5:20, 15:16; **25:** 1:12, 11:07, 21:03; **26:** 6:59, 16:55; **27:** 2:51, 12:47, 22:42; **28:** 8:38, 18:34

March 1: 4:33, 14:29; **2:** 0:25, 10:21, 20:16; **3:** 6:12, 16:08; **4:** 2:04, 12:00, 21:56; **5:** 7:52, 17:47; **6:** 3:43,

Jupiter's Moons



13:39, 23:35; **7**: 9:31, 19:27; **8**: 5:23, 15:18; **9**: 1:14, 11:10, 21:06; **10**: 7:02, 16:58; **11**: 2:54, 12:50, 22:45; **12**: 8:41, 18:37; **13**: 4:33, 14:29; **14**: 0:25, 10:21, 20:16; **15**: 6:12, 16:08; **16**: 2:04, 12:00, 21:56; **17**: 7:52, 17:47; **18**: 3:43, 13:39, 23:35; **19**: 9:31, 19:27; **20**: 5:23, 15:18; **21**: 1:14, 11:10, 21:06; **22**: 7:02, 16:58; **23**: 2:54, 12:49, 22:45; **24**: 8:41, 18:37; **25**: 4:33, 14:29; **26**: 0:24, 10:20, 20:16;

27: 6:12, 16:08; **28**: 2:04, 12:00, 21:55; **29**: 7:51, 17:47; **30**: 3:43, 13:39, 23:35; **31**: 9:31, 19:26

These times assume that the spot will be centered at System II longitude 36° on March 1st. If the Red Spot has moved elsewhere, it will transit 1½ minutes earlier for each degree less than 36° and 1½ minutes later for each degree more than 36°.

Phenomena of Jupiter's Moons, March 2023

Mar. 1	3:56	III.Oc.D	13:25	III.Ec.R	12:41	I.Tr.I	Mar. 24	11:52	I.Oc.D	
	6:44	III.Oc.R	16:05	I.Ec.R	13:09	I.Sh.I		14:24	I.Ec.R	
	7:00	III.Ec.D	Mar. 9	2:09	II.Oc.D	14:53	I.Tr.E	Mar. 25	2:08	II.Tr.I
	9:24	III.Ec.R		5:47	II.Ec.R	15:20	I.Sh.E		2:49	II.Sh.I
	11:14	I.Oc.D		10:38	I.Tr.I	Mar. 17	9:49	I.Oc.D	4:38	II.Tr.E
	14:10	I.Ec.R		11:14	I.Sh.I		12:29	I.Ec.R	5:13	II.Sh.E
	23:18	II.Oc.D		12:51	I.Tr.E		23:15	II.Tr.I	9:13	I.Tr.I
Mar. 2	3:10	II.Ec.R		13:25	I.Sh.E				9:32	I.Sh.I
	8:36	I.Tr.I	Mar. 10	7:47	I.Oc.D				11:26	I.Tr.E
	9:18	I.Sh.I		10:34	I.Ec.R				11:44	I.Sh.E
	10:50	I.Tr.E		20:23	II.Tr.I			Mar. 26	6:23	I.Oc.D
	11:30	I.Sh.E		21:33	II.Sh.I				8:01	III.Tr.I
Mar. 3	5:45	I.Oc.D		22:54	II.Tr.E				8:53	I.Ec.R
	8:39	I.Ec.R		23:58	II.Sh.E				9:22	III.Sh.I
	17:32	II.Tr.I	Mar. 11	5:09	I.Tr.I	Mar. 19	3:28	III.Tr.I	10:39	III.Tr.E
	18:56	II.Sh.I		5:42	I.Sh.I		4:20	I.Oc.D	11:40	III.Sh.E
	20:03	II.Tr.E		7:22	I.Tr.E		5:19	III.Sh.I	21:16	II.Oc.D
	21:20	II.Sh.E		7:54	I.Sh.E	Mar. 27	0:17	II.Ec.R	0:17	II.Ec.R
Mar. 4	3:07	I.Tr.I		22:55	III.Tr.I		6:09	III.Tr.E	3:44	I.Tr.I
	3:47	I.Sh.I	Mar. 12	1:16	III.Sh.I		6:58	I.Ec.R	4:01	I.Sh.I
	5:20	I.Tr.E		1:38	III.Tr.E		7:39	III.Sh.E	5:57	I.Tr.E
	5:58	I.Sh.E		2:18	I.Oc.D		18:25	II.Oc.D	6:12	I.Sh.E
	18:24	III.Tr.I		3:37	III.Sh.E	Mar. 28	0:53	I.Oc.D	18:04	II.Tr.E
	21:09	III.Tr.E		5:03	I.Ec.R		2:06	I.Sh.I	3:22	I.Ec.R
	21:14	III.Sh.I		15:34	II.Oc.D		3:54	I.Tr.E	15:34	II.Tr.I
	23:36	III.Sh.E		19:05	II.Ec.R		4:17	I.Sh.E	16:08	II.Sh.I
Mar. 5	0:15	I.Oc.D		23:40	I.Tr.I		22:51	I.Oc.D	18:04	II.Tr.E
	3:07	I.Ec.R	Mar. 13	0:11	I.Sh.I	Mar. 21	1:27	I.Ec.R	18:32	II.Sh.E
	12:43	II.Oc.D		1:52	I.Tr.E		12:41	II.Tr.I	22:15	I.Tr.I
	16:29	II.Ec.R		2:22	I.Sh.E		13:30	I.Sh.I	22:30	I.Sh.I
	21:37	I.Tr.I		20:48	I.Oc.D	Mar. 29	15:12	II.Tr.E	20:12	I.Tr.I
	22:16	I.Sh.I		23:32	I.Ec.R		15:54	II.Sh.E	20:35	I.Sh.I
	23:50	I.Tr.E	Mar. 14	9:49	II.Tr.I		20:46	I.Sh.E	22:25	II.Tr.E
Mar. 6	0:27	I.Sh.E		10:52	II.Sh.I		21:46	I.Oc.D	21:51	I.Ec.R
	18:46	I.Oc.D		12:20	II.Tr.E	Mar. 30	17:21	I.Oc.D	22:05	III.Oc.D
	21:36	I.Ec.R		13:17	II.Sh.E		17:31	III.Oc.D	10:42	II.Oc.D
Mar. 7	6:57	II.Tr.I		18:10	I.Tr.I		19:56	I.Ec.R	13:35	II.Ec.R
	8:14	II.Sh.I		18:40	I.Sh.I	Mar. 22	20:23	I.Tr.E	16:45	I.Tr.I
	9:28	II.Tr.E		20:23	I.Tr.E		21:26	III.Ec.R	16:59	I.Sh.I
	10:39	II.Sh.E		20:51	I.Sh.E	Mar. 23	7:51	II.Oc.D	18:58	I.Tr.E
	16:08	I.Tr.I	Mar. 15	12:58	III.Oc.D		10:59	II.Ec.R	19:10	I.Sh.E
	16:45	I.Sh.I		15:19	I.Oc.D	Mar. 24	14:43	I.Tr.I		
	18:21	I.Tr.E		17:25	III.Ec.R		15:04	I.Sh.I		
	18:56	I.Sh.E		18:00	I.Ec.R	Mar. 25	16:56	I.Tr.E		
Mar. 8	8:27	III.Oc.D	Mar. 16	5:00	II.Oc.D		17:15	I.Sh.E		
	13:16	I.Oc.D		8:23	II.Ec.R	Mar. 26				

Every day, interesting events happen between Jupiter's satellites and the planet's disk or shadow. The first column gives the date and mid-time of the event, in Universal Time (which is 5 hours ahead of Eastern Standard Time). Next is the satellite involved: **I** for Io, **II** Europa, **III** Ganymede, or **IV** Callisto. Next is the type of event: **Oc** for an occultation of the satellite behind Jupiter's limb, **Ec** for an eclipse by Jupiter's shadow, **Tr** for a transit across the planet's face, or **Sh** for the satellite casting its own shadow onto Jupiter. An occultation or eclipse begins when the satellite disappears (**D**) and ends when it reappears (**R**). A transit or shadow passage begins at ingress (**I**) and ends at egress (**E**). Each event is gradual, taking up to several minutes. Predictions courtesy IMCCE / Paris Observatory.

The wavy lines represent Jupiter's four big satellites. The central vertical band is Jupiter itself. Each gray or black horizontal band is one day, from 0^h (upper edge of band) to 24^h UT (GMT). UT dates are at left. Slide a paper's edge down to your date and time, and read across to see the satellites' positions east or west of Jupiter.



Hunting for Venusian Fireballs

Is it possible to see meteors on the nightside of our sister planet?

For well over a century, visual observers have reported transient flashes of light on the Moon's nightside and within the shadowed portion of lunar craters. These fleeting points of light were widely regarded as meteoroid impacts, but it wasn't until 1999 that they were first conclusively recorded using sensitive black-and-white video cameras paired with surprisingly small telescopes. Free software that automatically scans lunar videos to detect these flashes soon followed, eliminating the tedious task of examining hours of video recordings frame by frame. Since then, a network of amateur and professional astronomers who keep watch on the Moon's nightside has documented

hundreds of impact flashes. The valuable data amassed by this collaborative effort shed light on both the size and nature of the meteoroid population and help to assess the hazards posed to crewed and robotic spacecraft.

The Moon is an essentially airless body, so meteoroids strike its surface with undiminished velocities as high as 70 kilometers (43 miles) per second. When a meteoroid smacks into the lunar surface, the lion's share of the impactor's kinetic energy excavates a crater or is converted into heat. Only a minuscule fraction (recent models suggest as little as 0.2%) is transformed into visible light to produce a flash that appears at the point of impact. A piece

◀ Venus's vast nightside presents a virtually untapped resource for observers watching for impactors burning up in the planet's dense atmosphere.

of cosmic debris the size of a beach ball traveling at 25 km/s delivers the explosive equivalent of 5 tons of TNT, but to an earthbound observer the flash it produces looks only as bright as a fourth-magnitude star.

The nightside of a 5-day-old (24%-illuminated) crescent Moon provides almost 14.3 million square km of surface area to monitor for impacts. When Venus presents a similar phase, the visible area of its nightside is about 12 times larger than the Moon's. The apparent angular size of Venus varies from about 30" when its crescent is 40% sunlit to about 40" when it is 20% sunlit, so a magnification of 200× makes the planet appear about four times larger than the Moon as seen with the naked eye.

Unlike the Moon, Venus has a deep, dense atmosphere. When meteoroids enter the tenuous outer reaches of Earth's atmosphere, they begin to glow at altitudes of 80 to 120 km, producing a meteor's incandescent streak of light. Due to Venus's massive, distended atmosphere, calculations suggest Venusian meteors should start to burn up at altitudes of 250 to 300 km — far above the planet's thick blanket of clouds, which extends to an altitude of 65 km. So, a telescopic observer has an excellent vantage point. The almost subliminal flash of a lunar impact usually lasts only 10 to 100 milliseconds, but the light bolides emit in the atmosphere of Venus should be of considerably longer duration — they streak through the atmosphere as they burn up, rather than smashing into the surface as we see on the Moon.

In 2009, astronomer Brian Cudnik of Prairie View A&M University in Texas suggested that Venus "presents the best opportunity after the Moon to spot impacts on another world," yet our sister planet is sorely neglected in this regard despite its relatively close proximity and our ability to see its nightside.

In 1995, University of Western

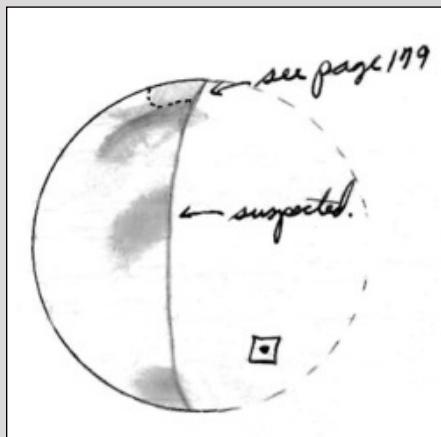
Ontario astronomers Martin Beech and Peter Brown suggested that fireballs on the nightside of Venus bright enough to be seen through amateur telescopes ought to occur once every three to four days — an estimate based on the assumption that Venus encounters fireball-producing meteoroids with the same frequency that Earth does.

Despite this prediction, I've only managed to turn up two convincing observations of Venusian fireballs. The first was made by a distinguished NASA planetary scientist, Dale Cruikshank. On July 11, 1959, when he was a 20-year-old undergraduate student, Cruikshank was observing Venus in broad daylight through the 40-inch Yerkes refractor when a sparkle caught his eye. The following note from his observing notebook accompanies the sketch of the 38%-illuminated Venusian crescent:

The small dot in the box on the night side of the planet marks the position of a very small, bright spot which appeared to me at 18:19 UT. It persisted only for about ¼ to ½ second and reached maximum brilliancy at the half-way point. There was no motion connected with the spot of light. At maximum brilliancy the point of light was comparable with the bright limb of the planet. I truly think that this was a real object, perhaps a meteor in the upper atmosphere of the planet or perhaps in our own, although the former appears the mostly like [sic] because of the absence of apparent motion of the bright spot. I watched for a recurrence but saw nothing. Most peculiar.

When I contacted Cruikshank early last year to discuss the 1959 observation, he commented: "I have never seen anything comparable on any other planet. . . Whether or not that bright spot was an illusion (always possible), the fact that similar flashes have been recorded in CCD and other objective images of Jupiter and the Moon at least lends some credibility to the Venus flash."

The second observation I found was made on October 8, 1959, when Venus



▲ Dale Cruikshank sketched the above bright point (within the box) seen on Venus's unlit hemisphere while observing during daylight hours on July 11, 1959.

was a 28%-illuminated crescent. Using a 12-inch Newtonian at 200× to 300× in very good seeing, British observer Valdemar Firsoff saw a "... bright light, as though a faint star . . . on the limb about 20° beyond the point of the north cusp" on the planet's nightside. He compared it to a flare.

Is the dearth of Venusian fireball reports simply due to a failure to look for them? Amateurs could record potential impacts using many of the same tools and techniques used to record impacts on the lunar nightside. In fact, amateurs have captured 9 impact flashes

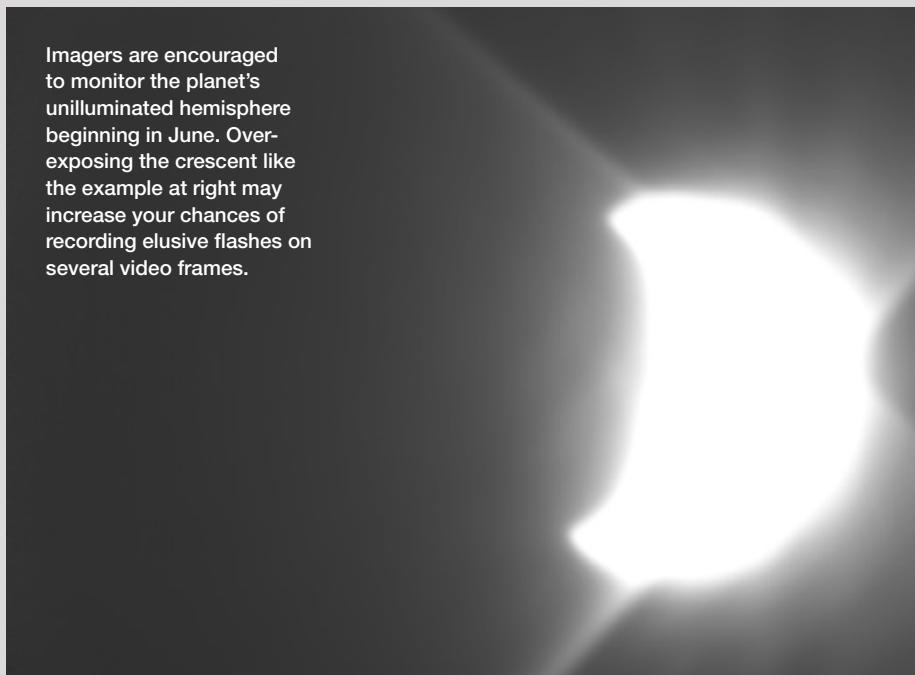
Imagers are encouraged to monitor the planet's unilluminated hemisphere beginning in June. Over-exposing the crescent like the example at right may increase your chances of recording elusive flashes on several video frames.

on Jupiter's sunlit canopy using the same technique (S&T: Jan. 2022, p. 52).

For observers in the Northern Hemisphere, the late spring and early summer of 2023 present an unusually favorable opportunity for mounting a search. From 40°N latitude, Venus's 42%-illuminated crescent will stand 32° above the horizon at sunset on June 16th. By July 7th, the illuminated crescent shrinks to 27%, though the planet's altitude at sunset decreases to 22°.

Readers should take advantage of this three-week observing window to carefully monitor the Venusian nightside either visually or with video. Cruikshank's daytime sighting of a flash suggests that observing well before sunset may be worthwhile as the planet is higher above the horizon. Simultaneous video recordings by observers in widely separated locations can eliminate sources of deception such as a "point meteor" in Earth's atmosphere headed directly at an observer, sunlight glinting off a foreground satellite or orbital debris, and electronic noise that can masquerade as a flash in a video recording. Good luck!

■ Contributing Editor TOM DOBBINS has yet to witness an object hit a body in the solar system himself.



Best Foot Forward

Deep-sky treasures abound in the westernmost foot of Gemini.

Mid-March. Nightfall. I face south and gaze way up to admire the stars Castor and Pollux, 4.5° apart in the constellation Gemini, the Twins. Gemini's roughly rectangular pattern

embodies two brothers standing side-by-side in the heavens with 1.6-magnitude Castor and 1.1-magnitude Pollux serving as the boys' celestial visages. Heady stuff, but I'm shifting my atten-



tion to the fainter stars representing Castor's western foot.

That bit of anatomy, symbolized by 3.3-magnitude Eta (η) Geminorum, is named Propus, which means "forward foot." My vivid imagination provides more detail: The heel is 2.9-magnitude Mu (μ), and the toes are 4.2-magnitude 1 Geminorum. The three stars form a bent east-west row, 4.4° long — if I can see them. Eta and Mu are easy, but 1 Gem is barely visible in my light-polluted suburban sky.

So why all the fuss over a foot?

The answer lies in the Milky Way, which flows across the southern half of Gemini. The star-rich galactic equator runs right past 1 Gem. In my mind's eye, I see young Castor dipping his toes into a deep pool of Milky Way stars. Local light pollution prevents me from appreciating this pool with my unaided eyes, but it's a delight to examine in a backyard telescope.

Join me on a heel-to-toe examination of Castor's western foot. I'm using a 120-mm (4.7-inch) f/7.5 apochromatic refractor, though any 4- or 5-inch scope of good quality will do.

Foot Fare

Our exploration begins at **Eta Geminorum**. Eta is a long-period variable star and a challenging binary catalogued as BU 1008. Its 6.2-magnitude B component is just 1.8" westward. I've never tried to split Eta before and, alas, the wee B is a no-show in my apo. However, Eta slowly ranges from magnitude 3.1 to 3.7 over a span of 234 days. Eta is bright tonight, but when it's near minimum the pair should be easier to resolve. I plan on trying the Eta Challenge again.

A 30-mm, wide-angle eyepiece on my refractor generates a 2° field of view at

► **UNALIKE CLUSTERS** The prominent open cluster M35 is located in the western foot of Gemini, the Twins. Although nearly 3,000 light-years from Earth, the object is an easy binocular object and glorious in any size of telescope. Of the many fine clusters in the winter Milky Way, this is the author's favorite. Sharing the telescope field is the much dimmer but more populous NGC 2158, which is at least four times farther away than M35.

30×. That's just good enough to frame Eta and Mu Gem, which lie 1.9° apart, aligned east-west. Old star lore refers to Eta as Tejat Prior and Mu as Tejat Posterior. Prior and Posterior make sense (because Eta leads Mu across the sky) but, oddly, the name Tejat itself has no obvious meaning. Both Tejats burn beautifully orange in my scope. For another variable, I push ¾° northwest of Eta to 6th-magnitude **BU Geminorum** (aka 6 Gem). BU exudes a lovely reddish hue.

Just north of the Tejat twosome is **Collinder 89**, an underwhelming open cluster 1° across. Cr 89 contains 15 stars (whoopee!), and my scope at 30× captures the entire scatter. A modest highlight of Cr 89 is a ¼°-wide quadrilateral of stars at its southeastern end.

The Quad's southeastern corner is marked by a double cataloged as **BNW 3**, which comprises 8.7- and 9.3-magnitude stars 57.8" apart. The southwestern corner is emblazoned by 7.0-magnitude 12 Gem, which is the primary element of an unequal duo named **H V 55**. Its 10.8-magni-

tude partner lies 62.1" northeastward. Halfway between the two southern corners is a 9.4-magnitude star with a 10.9-magnitude attendant. The fainter stars in both pairs are unremarkable at 30× but perk up nicely at 50×.

I next shift northwestward to the toe-end of Castor's "forward foot." Returning to 30×, I scan from BNW 3 diagonally northwest across the Quad to 7th-magnitude 11 Gem, then onwards past 10, 9, and 8 Gem to 5 Gem. Between those last two stars I pause at a spacious double called **STTA 70**. Its 7.6- and 8.0-magnitude stars, lined up north-south, are separated by a generous 114.4".

Glitter and a Ghost

Veering westward ½° past 5 Gem, I come to a true gem of an open cluster — **M35**. Almost 3,000 light-years from Earth, M35 is a touch less than ½° in diameter and glitters impressively at magnitude 5.1. The cluster contains in excess of 400 blue-white stars. At least three-dozen cluster members, 8th-magnitude and fainter,

show in my suburban scope at 30× — twice that many are visible at higher magnifications.

A particularly striking feature of M35 is a 6'-long crescent formation near the cluster's northern edge. The crescent's northeastern tip is established by **Ω134**, a colorful double sporting a 7.6-magnitude yellow sun and 9.1-magnitude blue-white companion 31" apart. The opposite end of the arc is marked by an 8.2-magnitude star; 30× produces three dimmer stars (and hints of more) within the crescent. When I avert my vision away from M35, the half-dozen dots blur into a gleaming curve. It's an amazing effect.

The can't-miss crescent in M35 resembles a smile or a frown, depending on the configuration of your telescope. My diagonal-equipped refractor presents north up, so M35 gives me a smile. At 50×, the broad grin boasts 10 toothy stars; 100× confirms that number and resolves the dental details into an 11th-magnitude binary at mid-mouth plus a minuscule isosceles triangle beside the southwestern end. Patient star-



▲ **CASTOR'S FAVORITE FOOT** Eta (η) Geminorum, or Propus, meaning "forward foot," is the staging point for exploring several interesting open clusters and double stars visible across this small region in western Gemini.



ing at 129× rewards me with two more diminutive dots, for a total of 12 stellar teeth. At 129×, the smiling cluster spans the entire eyepiece field.

M35 has a deep-sky neighbor lying less than $\frac{1}{4}^\circ$ southwest: **NGC 2158**. The little open cluster packs twice the population of M35, yet it's only 5' in diameter

and glows weakly at magnitude 8.6. The reason? NGC 2158 is more than four times farther away than M35. Detecting this distant cluster in my backyard optics requires some careful scoping.

Starting safely at 30×, I look just beyond the southwest edge of M35 to a Y-shaped asterism of six 10th-mag-

itude stars, as shown in the photo on page 54. The stem of the Y points toward NGC 2158; indeed, it almost touches the pallid prize. Upping the magnification to 50× slightly brightens the mist, and at 100× it exhibits a grainy texture. At 129×, the granular effect is stronger, suggesting a powder of stars too dense to be resolved. A single 10.7-magnitude pinpoint in the southeastern part of the powder is visible at the threshold of vision. Not bad for a city sky.

To the Toes

Defaulting to 30× again, I hop 1° southwestward to 1 Gem, my “toes” star. From there, I turn sharply northwestward for $\frac{3}{4}^\circ$ to sight the first of two essentially identical tandems, the second set lying less than $\frac{1}{2}^\circ$ southward of the first. Each tandem consists of 7th- and 8th-magnitude stars approximately 2' apart, aligned basically north-south. The unofficial doubles are labelled Pair A and Pair B on the chart on page 55. I picture these four stars as representing — in cartoon fashion — the four toenails of Castor's forward foot. The toes star and four toenails make a pretty field.

But wait — the 30× view picks up a few speckles of light around the northern component of Pair B. At 50×, I count six specks surrounding both components. The number increases to eight at 100× and 10 at 129×. Hey, this is a cluster! Pair B appears to overlie **NGC 2129**, a compact cluster of fewer than 100 stars. NGC 2129 is officially magnitude 6.7 but that includes Pair B; the clump by itself is a measly magnitude 8.2. Even so, NGC 2129 is an easier catch than NGC 2158.

Grab your scope the next clear night and visit Gemini's forward foot. You'll get a kick out of what you find there.

■ Whether it's smiling or frowning, M35 makes Contributing Editor **KEN HEWITT-WHITE** a happy observer.

Underfoot Finds

Object	Type	Mag(v)	Size/Sep/Per	RA	Dec.
η Gem	Double star	~3.5, 6.2	1.8"	06 ^h 14.9 ^m	+22° 30'
BU Gem	Variable star	4.7, 5.5	460 days	06 ^h 12.3 ^m	+22° 55'
Cr 89	Open cluster	5.7	~1°	06 ^h 19.5 ^m	+23° 18'
BNW 3	Double star	8.7, 9.3	57.8"	06 ^h 19.9 ^m	+23° 16'
H V 55	Double star	7.0, 10.8	62.1"	06 ^h 19.4 ^m	+23° 16'
STTA 70	Double star	7.6, 8.0	114.4"	06 ^h 14.1 ^m	+23° 59'
M35	Open cluster	5.1	25.0'	06 ^h 09.0 ^m	+24° 21'
OΣ134	Double star	7.6, 9.1	31.0"	06 ^h 09.3 ^m	+24° 26'
NGC 2158	Open cluster	8.6	5.0'	06 ^h 07.4 ^m	+24° 06'
NGC 2129	Open cluster	6.7	6.0'	06 ^h 01.1 ^m	+23° 19'

Angular sizes and separations are from recent catalogs. Visually, an object's size is often smaller than the cataloged value and varies according to the aperture and magnification of the viewing instrument. Right ascension and declination are for equinox 2000.0.



Star Notes

Join a project dedicated to preserving logbooks of yore.

For most of astronomy's history, observers recorded what they saw at the eyepiece by jotting down notes, sketching, or both. These methods can be subjective, leading to eclectic interpretations of the science of the skies. But they nevertheless afforded us the only view of the universe until the early 19th century, when a new, more accurate technique of recording celestial phenomena arrived on the scene: photography.

Glass plates and women computers. By the time Edward Charles Pickering became the fourth director of Harvard College Observatory (HCO) in 1877, astronomical photography with the famed 15-inch Great Refractor had practically become routine. Pickering launched ambitious projects dedicated to observing the sky, both photometrically and spectroscopically. So ambitious was he, in fact, that he established an observatory in Arequipa, Peru, to cover the Southern Hemisphere sky. Soon, Pickering and his staff were inundated with photographic glass plates . . . and valuable astronomical data. And so he started hiring assistants to curate the overflowing glass-plate collection — and for that he turned to women.

The Harvard Computers (as they came to be known) did so much more, though. Pickering's Scottish housemaid, Williamina Fleming — whom he later nominated to be the HCO's first Curator of Astronomical Photographs — dis-

covered the Horsehead Nebula, and her name lives on in a wisp of the Cygnus Loop (S&T: Sept. 2021, p. 30). We owe our current method of stellar classification to Annie Jump Cannon, who also identified more than 300 variable stars. Henrietta Swan Leavitt formulated the Cepheid period-luminosity relationship (S&T: Dec. 2021, p. 12), while Cecilia Payne-Gaposchkin deciphered the chemical composition of stars.

These four are the Computers you've most likely heard of. Countless others who contributed to our fundamental understanding of the universe have largely gone unrecognized. But existing endeavors aim to rectify this.

DASCH it all. By the late 1980s, HCO had amassed more than half a million photographic glass plates — the world's largest collection. The vitreous surfaces aren't only peppered with the dots and splotches of stars, nebulae, and galaxies, but also the meticulous notes, musings, and calculations of the women who analyzed them. To preserve this precious material, the Digital Access to a Sky Century at Harvard (DASCH) project is digitizing the glass plates for posterity. In addition, the century-plus of data allows for the systematic study of variability in myriad objects on time scales ranging from days to decades.

But there's a second, priceless piece to the collection: the Computers' logbooks.

Plans to preserve. The entity that houses the glass plates, the Wolbach Library, launched Project PHAEDRA (Preserving Harvard's Early Data and Research in Astronomy) to collate and conserve the valuable information contained in the Harvard Computers' notebooks. One component

▲ **INSPIRATION FOR ALL** Volunteers are helping preserve some 2,500 notebooks that Harvard astronomers, including the Computers, kept between 1750 and 1990.

of this project is Star Notes. Phase 1 (completed) identified plate numbers in the logbooks, which link them to the digitized DASCH material. Phase 2 (currently underway) aims to catalog elements that are non-textual, such as sketches and hand-drawn diagrams and charts. Besides the Computers' logbooks, volunteers will also scour material from before the photographic era, dating back to 1750 or so. Says Nico Carver, Wolbach's Librarian for Collaborative Programs, "This phase is akin to a scavenger hunt, as most pages do not have sketches, but it is exciting to find them when they pop up!"

You'll need nothing more than a dash of historical curiosity and an internet connection to participate. Head over to https://is.gd/star_notes and study the tutorial for guidelines. "Volunteers can expect to help us better understand what is hidden within these valuable notebooks," says Carver. "For those who want to dig deeper, we can connect them to resources and support their research." Should your fingers be itchy, you can also partake in Project PHAEDRA's transcription endeavor (https://is.gd/phaedra_transcription). By participating, you'll not only directly commune with the history of astronomy, but you'll also preserve the legacy of hundreds of hardworking, largely forgotten astronomers.

■ **DIANA HANNIKAINEN** is grateful that the hard work of the women astronomers of the 1800s is being preserved.

Stepping Up to CMOS

Upgrading to the latest cameras may require changing your imaging techniques.

Over the last decade, the deep-sky astrophotography industry has undergone rapid changes. The growth in the size and sensitivity of digital detectors, dominated until recently by charge-coupled devices (CCDs), fueled the rising popularity of fast, well-corrected astrographs that take advantage of these new detectors. This in turn helped to drive the development of computerized mounts and software to enable these scopes to record deep, colorful images of the universe around us.

CCDs had a good run, but inevitably a newer detector emerged and quickly rose to prominence. Complementary metal-oxide-semiconductor (CMOS) detectors, which are less expensive and easier to manufacture, became the dominant detector in popular consumer electronics such as digital cameras and smartphones. The explosive growth in these markets drove trends in the much smaller astronomical community.

So, it wasn't a big surprise when at the end of the last decade, the largest manufacturers of CCD detectors announced they would cease production. At the time, CMOS performance wasn't thought to be quite ready to match CCDs, suffering from issues with amp glow and read noise that made them less than ideal for deep-sky imaging (S&T: May 2020, p. 30). Fortunately, astronomical-camera manufacturers made tremendous strides, and just a few short years later, CMOS technology has improved dramatically.

What does that mean for deep-sky imagers contemplating switching from CCD to CMOS? Let's have a look.

Differences Between CCD and CMOS

On the surface, there aren't a lot of differences between CCD and CMOS technologies. Both sensors consist of an array of photosensitive sites called *photosites*. To create a



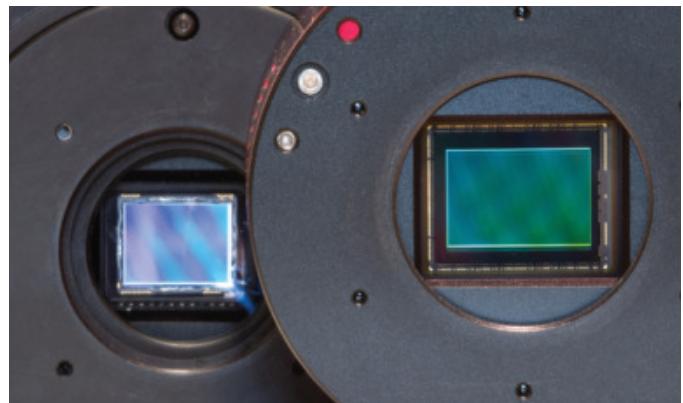
PICTURE PERFECT Pretty much any astronomical camera can take wonderful images of the night sky, but CCD technology is being phased out in favor of CMOS sensors. The author looks at the benefits of upgrading your old CCD camera in order to record deep, colorful portraits of the night sky, such as this composition that includes the Heart and Soul nebulae in Cassiopeia.

picture, the detector records the number of photons striking each photosite, generating electrons that are then counted and read from the sensor at the end of the exposure, turning the signal into picture elements or *pixels*. (For simplicity, we'll refer to photosites hereafter as pixels.) In a perfect world, the electron counts would exactly match the number of incoming photons from our targets, and our images would be clean and smooth.

Unfortunately, all electronic sensors are imperfect. The process of reading out the image signal produces noise (called *read noise*). In addition, the sensitivity of a detector is never 100%, so it doesn't turn every photon into an electron. The percentage of photons converted to electrons is known as the detector's *quantum efficiency*.

On average, CMOS sensors have reached parity with CCDs in terms of quantum efficiency, though many are both

more sensitive and less costly than their CCD predecessors. But it's in the realm of noise management where CMOS sensors — particularly the latest generation — are now taking the lead. CMOS cameras generally produce much less dark current than even the best CCDs for a given temperature. Some of the latest sensors have such negligible levels of read noise that its contribution is inconsequential in the final images produced. Additionally, the major hurdle of *amp glow* (a heat-generated signal from the associated circuit board that bleeds onto the detector) appears to be a thing of the past. This opens up new possibilities in deep-sky image-acquisition techniques. With such low read noise, imagers



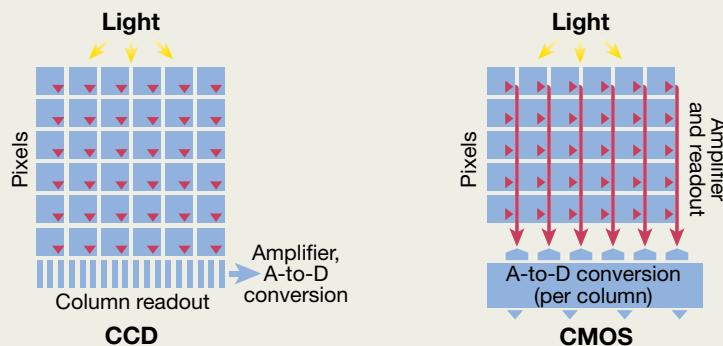
▲ **CCD OR CMOS?** It's nearly impossible to see the difference between the charge-coupled detector (CCD) in the SBIG ST-8300 camera at left and the complementary metal-oxide-semiconductor (CMOS) seen in the ZWO ASI2600MC PRO camera at right.

now can combine many short exposures made with a CMOS camera for a combined result that's not dominated by read noise. Deep-sky photos produced this way will be as good as, or better than, a few long exposures acquired with a CCD (or previous-generation CMOS) camera.

Another big difference between CCD and CMOS sensors is the size of the pixels. On average, CMOS deep-sky cameras have much smaller pixels compared to those found in CCD cameras. The last, fairly large CCD detectors in deep-sky cameras typically had 6-micron or larger pixels. CMOS sensors, on the other hand, often come with pixels in the range of 2 to 4 microns. Conventional wisdom states that larger pixels gather more light, just as a larger bucket would collect more rain in a downpour. But that, too, is no longer a given. The lack of appreciable read noise, combined with high quantum efficiency, and a few other tricks like microlens technology to steer light onto the photosensitive area of each pixel, mean these differences are less of a concern.

Finally, the biggest distinction between CCD and CMOS detectors is in the way the data are read after an exposure. CCDs must transfer the recorded signal off the detector in rows. The electrons are then sent off-chip to the amplifier and analog-to-digital (A-to-D) converter. With few exceptions, CCD cameras were designed with a USB 2.0 computer interface, resulting in fairly slow download speeds. By

► **INTERNAL DIFFERENCES** Although CCD and CMOS chips function in largely the same way, one important difference is how they read out signal. A CCD (near right) moves electrons (red arrows) off the detector in rows. The electrons are then sent off-chip to the amplifier and analog-to-digital converter. By contrast, the CMOS detector (far right) has an amplifier behind every pixel and an A-to-D converter for each column.



contrast, CMOS detectors incorporate an amplifier behind every pixel and an A-to-D converter for each column. This, combined with a fast USB 3.0 interface, means large amounts of data download extremely fast. A good example is the QHY600M reviewed in our July 2020 issue (page 68) that downloads a 60-megapixel image in under 5 seconds. On top of that, the camera includes an internal buffer where data are stored as they're transferred, allowing the camera to begin the next exposure even before it completes transferring the previous one. These improvements can increase your imaging efficiency. Less time lost to data transfers means more time for recording photons. In my case, the difference works out to an additional 5-minute exposure per hour compared to when I used a USB 2.0 CCD camera.

What This Means for You

Taken together, how does all this affect your future imaging? Let's look at the possibilities.

If you've considered increasing the resolution of your

imaging setup, you might accomplish this by selecting a camera with smaller pixels than the one you currently use. Pixel size affects resolution, and since most CMOS sensors have smaller pixels than those found on CCDs, stepping up to a new camera can improve your resolution and image scale, but only to a point.

For example, I image through a Sky-Watcher Esprit 150-mm refractor, which has a focal length of 1,070 millimeters (42 inches). When I pair this with my SBIG STL-11000M CCD camera, which has 9-micron pixels, it produces an image scale of 1.73 arcseconds per pixel. The same scope yields 0.72 arcseconds per pixel when combined with my QHY600M CMOS camera and its 3.76-micron pixels. This results in a modest resolution gain in my system at the cost of a new camera.

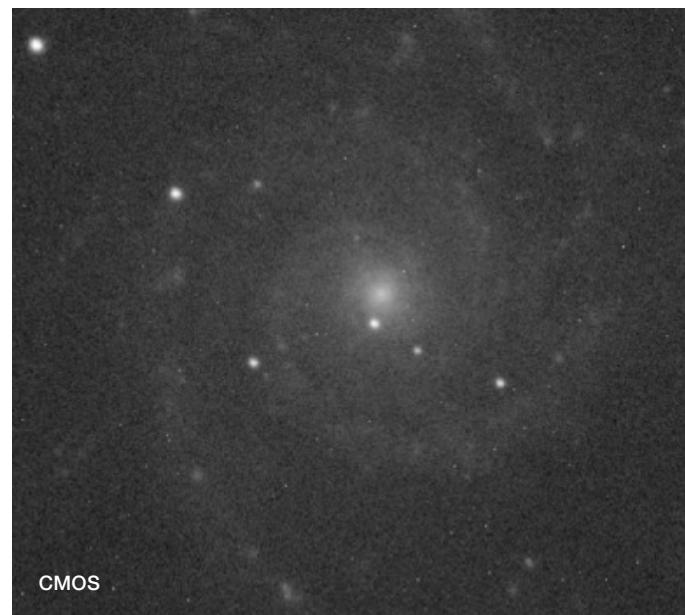
You can use the following formula to determine the arcseconds per pixel of any camera and telescope combination:

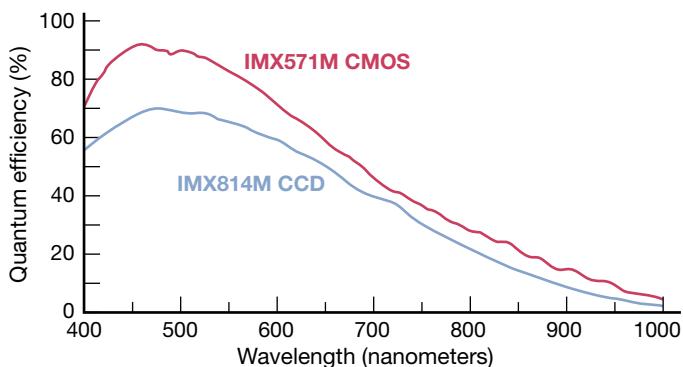
$$\text{Image scale} = \left(\frac{\text{pixel size}}{\text{focal length}} \right) \times 206.265$$

Pixel size is measured in microns, and the focal length is measured in millimeters.



▲ **THE DEVIL IS IN THE DETAILS** These uncalibrated 5-minute exposures of M74 were recorded through the same 6-inch refractor. The right image was captured with a QHY600M CMOS camera and displays less noise and far fewer hot pixels compared to the left image taken with a QHY16200A CCD model.





▲ **SHOOTOUT AT THE QE CORRAL** The newest CMOS detectors are typically more efficient at counting photons than most CCD sensors that amateurs use. This graph compares a popular CCD and CMOS sensor with similar-sized pixels in cameras manufactured by QHYCCD.

There are, of course, limits to this resolution trick. Firstly, one can potentially oversample the resolution possible with your optics and sky conditions. You don't gain anything if your local seeing rarely permits resolution of less than 2 arcseconds per pixel. You'll just have a bigger, blurrier image. Another problem may have to do with the spot size of your astrograph. Too small a pixel can begin to resolve optical aberrations in your system that weren't noticeable when you shot with a detector having larger pixels. (Don't worry, there's nothing actually wrong with your telescope.)

Goodbye to Guiding?

There are other ways a new CMOS camera can potentially simplify your imaging technique.

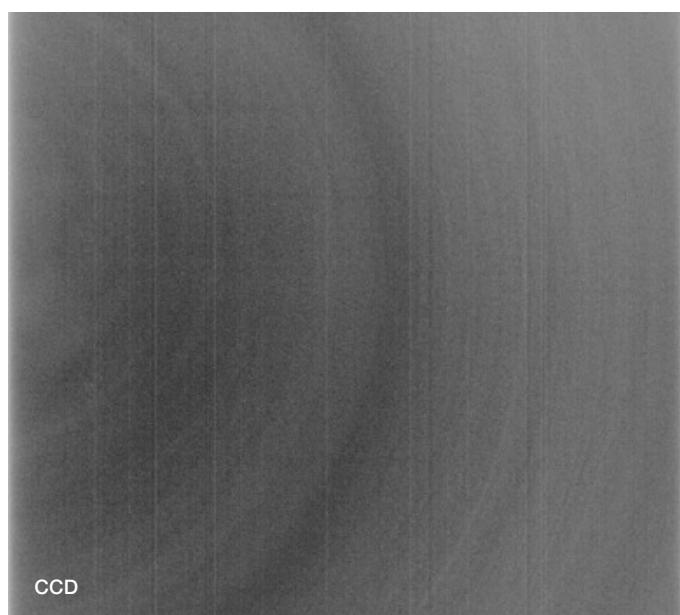
The lack of read noise with these detectors means exposures

can be short enough that autoguiding becomes less crucial and, in some cases, may be eliminated entirely.

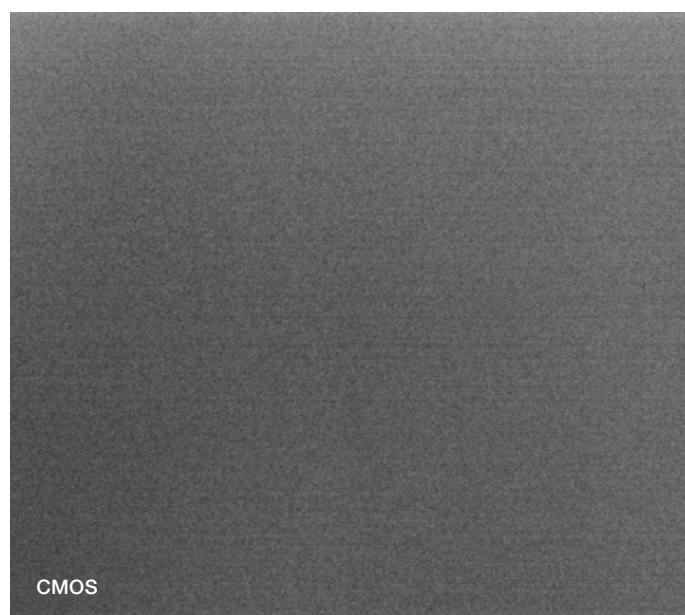
With these new cameras, you can take hundreds or even thousands of 1-minute exposures and simply stack them together to achieve an image just as deep and detailed as any produced with a CCD camera and sub-exposures of 20-minutes apiece. Most popular deep-sky image-processing software (including *PixelInsight* and *MaxIm DL*) can automatically discard any trailed images. And eliminating the need for a guidescope or off-axis guider, as well as a separate autoguiding camera and its cables, is particularly attractive to imagers who set up their equipment each night.

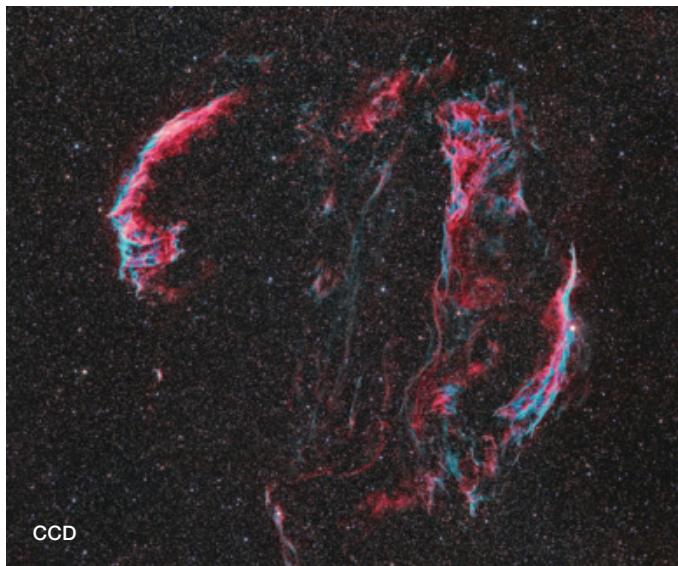
However, it's important to understand that this new approach does come with additional costs. Recording hundreds of 16-bit, full-frame images requires a lot of storage. In addition, you'll need a fairly robust processor and lots of RAM to reduce tens of gigabytes of data into a final image. This may mean upgrading to a new computer. As usual, there's no free lunch.

But aside from calibrating and stacking many more images, processing CMOS camera data is practically the same as for a CCD model. One approach that may not work for some CMOS cameras is to scale short dark frames to calibrate longer exposures. This was a useful shortcut that CCD imagers employed to avoid recording lots of various-length dark exposures (see *S&T*: Nov. 2019, p. 36). The technique permitted accurate scaling of long dark exposures by measuring the dark current and signal captured in a zero-length, or *bias*, exposure in order to be used to calibrate shorter light and flat-field calibration frames. However, this approach does not work well with some CMOS cameras. If your CMOS images show amp glow or don't calibrate well, try eliminating bias

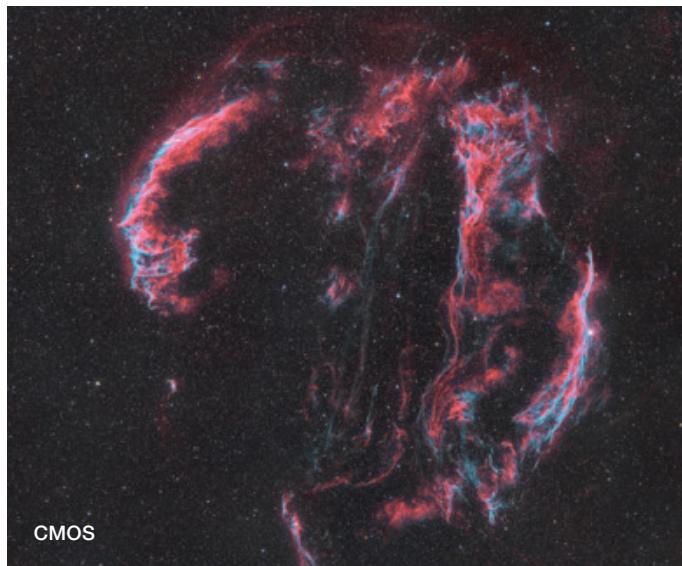


▲ **LOW NOISE** The 5-minute dark frame from a KAF 16803 CCD at left is processed to display light and dark lines that arise from subtle differences in sensitivity in the columns of the detector as well as a curved pattern resulting from an infrared flash needed to purge a residual bulk charge that plagued this and other large CCD detectors. None of these are visible in the 5-minute dark frame taken with an IMX455 CMOS sensor seen at right.



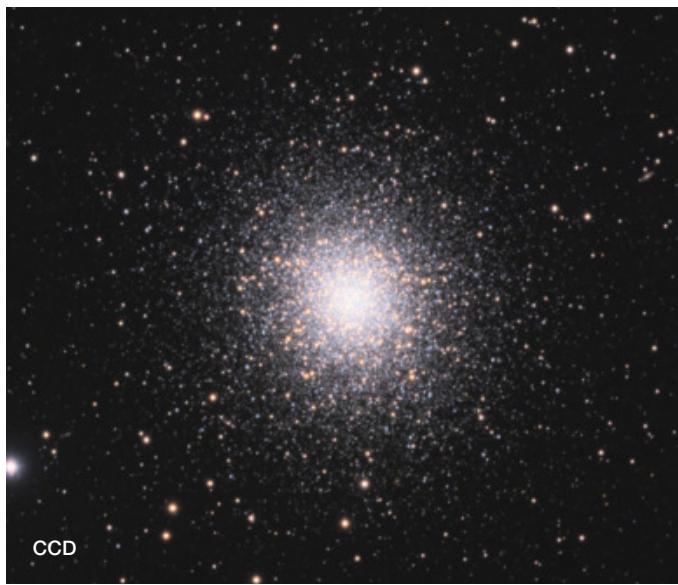


CCD

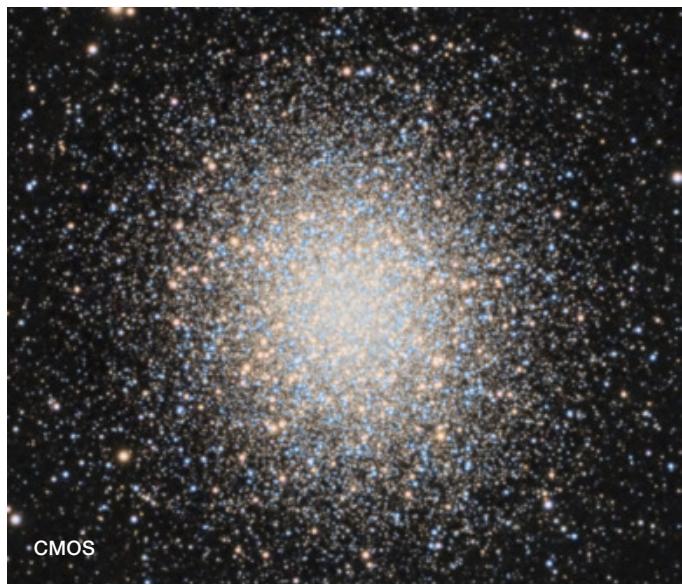


CMOS

▲ **NOT STEREO** Images created with either CCD or CMOS cameras can be equally attractive. The author recorded both of these pictures of the Veil Nebula supernova remnant through his 6-inch refractor, but he took the left photo using a QHY16200A monochrome CCD camera and color filters, while he shot the right image with a QHY367C-Pro with its color IMX094 CMOS sensor.



CCD



CMOS

▲ **RESOLUTION BOOST** The smaller pixels inherent in most CMOS detectors can resolve finer detail in your targets — it's almost like getting a larger telescope. However, there are limits to this effect. The photo of globular cluster M13 above left was recorded using the same telescope and CCD camera as the Veil Nebula pictures above. The CMOS image at right was made with a QHY600M with an IMX455 monochrome sensor.

frames from your workflow. You'll replace the bias frames with darks that exactly match your flats and lights.

Connecting the Dots

My astro-imaging friend Warren Keller often says "it's not the plane — it's the pilot," meaning that a good pilot can learn to fly any aircraft. The old deep-sky camera you currently own and are able to operate with solid acquisition and processing techniques will do a fine job as long as it's in good working order. Just look at some of the fantastic amateur and professional pictures many still produce today

with older equipment.

But when the time comes to upgrade — and that day will come eventually — consider moving to one of the latest cooled CMOS cameras instead of trading up for a new scope or mount. The powerful combination of high sensitivity, low noise, and lightning-fast download speeds of a new CMOS camera may be just the thing you need to kick your imaging up to the next level.

■ Contributing Editor RON BRECHER often hosts *PixInsight* image-processing workshops. Visit his website at astrodock.ca.

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Natasha Batalha,
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Natalie Batalha,
Ph.D.



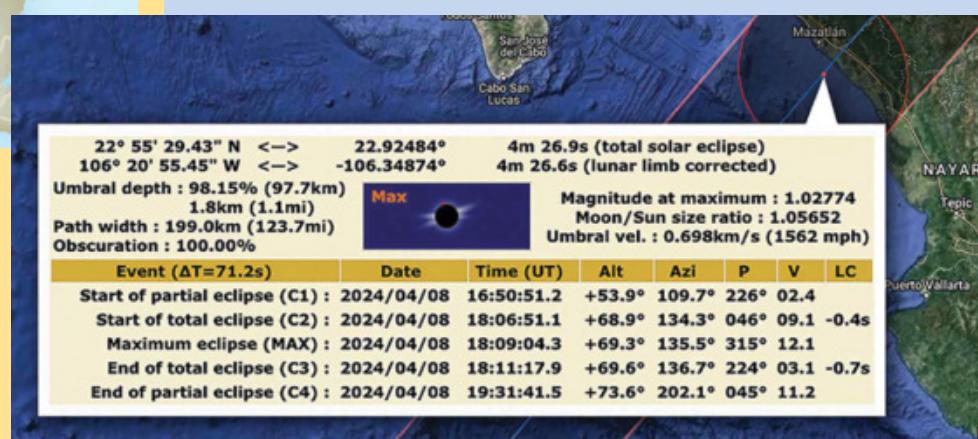
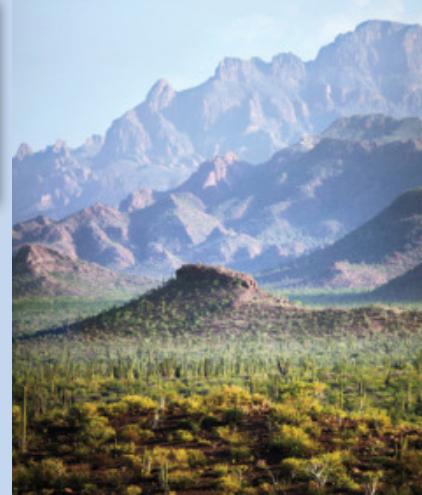
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What We Like

Excellent optical performance

Equally excellent mechanical construction

Noteworthy rotating focuser

What We Don't Like

Nothing

REFRACTORS HAVE ALWAYS held a special place in the hearts of amateur astronomers. I'm certainly not the only longtime *Sky & Telescope* reader who fondly remembers admiring the ads for Unitron refractors that graced the magazine's back cover during the 1950s, '60s, and early '70s. Back then there were only a few manufacturers offering what we would now call premium refractors. Today, however, there are dozens. And among those at the top of the list is California-based Stellarvue founded by Vic Maris.

Last summer and fall I spent several months using the Stellarvue SVX127D that we borrowed from the company for this review. It's a 127-mm (5-inch) f/8 apo refractor with an air-spaced doublet objective made with "super-low

► Stellarvue's SVX127D is a premium instrument that the author found superb for viewing solar system objects and multiple stars. The company's website offers extensive information on the scope's mechanical specifications, features, accessories, and user information.

dispersion and Lanthanum elements." It's from Stellarvue's line of what Maris promotes as hand-crafted telescopes with objectives manufactured and individually tested at the company's Auburn, California headquarters. Each scope's objective is guaranteed to be figured to at least a 0.99 Strehl ratio (more about this below) and is supplied with its Zygo test data attesting to the lens's quality. The scope I received for review has a 0.993 Strehl ratio.

While the mathematically complex Strehl ratio for assessing telescope optics has been around for more than a century, it's only recently been associated with telescopes intended for the amateur community, complementing the familiar "1/4-wave" criteria commonly cited as what's necessary for diffraction-limited optics. A Strehl ratio of 0.80 is considered diffraction limited, and the higher the ratio the better the optical performance. But what exactly does the Strehl ratio quantify? Simply put, it's the ratio of light collected by a telescope objective that's focused into the central core of a star's image (the Airy disk) compared with that of a theoretically perfect objective.

Expectations

Well before the SVX127D arrived on my doorstep for testing, Stellarvue's claimed Strehl ratio of 0.99 or better had set the bar pretty high for the optical performance I was expecting. And after months of observing the Sun, Moon, Venus, Saturn, Jupiter, and a slew of multiple stars, I'll flat out say I was never disappointed. There was noth-

ing about the optical performance that left me feeling that more could be had from a 127-mm aperture. The scope easily passed all the typical field tests that observers do to assess optical quality — no color halo around bright stars; identical star images inside and outside of focus; no hairline color fringes visible along the Moon's limb; perfect diffraction images of bright, in-focus stars; and the clean resolution of tight double stars.

And while on the topic of excellent performance, that goes for the SVX127D's optical tube assembly (OTA) as well. The machining, fit, finish, and overall construction are all first-rate. I tested the scope with Stellarvue's standard dual-speed, 3-inch rack-and-pinion focuser (for an additional \$500 an optional Feather Touch focuser is available). The focuser is attached to the OTA via a pair of extension rings having a total length of 80 mm. These can be removed by those observers planning to use the scope with a binoviewer.

The whole focuser body rotates so that the focus knobs can be positioned in a comfortable horizontal orientation regardless of where the scope is pointed when it's on an equatorial mount. While this is a common feature of high-end refractors, I found it particularly well done on the SVX127D. The rotational motion is exceptionally smooth, and there's enough friction to hold the focuser's position without using the

► The scope's doublet objective is supplied with detailed Zyglo test data attesting to its optical qualities and a guarantee of a Strehl ratio of at least 0.99. See the accompanying text for an explanation.

thumbscrew lock, even when there are heavy eyepieces on a star diagonal.

Inside the OTA there are four light baffles, and everything is coated with an ultra-flat black paint to suppress internal reflections from reaching an eyepiece or camera. I found no sign of reflections even when observing with a bright Moon just beyond the field of view.

Taking It Outside

The bare-bones SVX127D OTA weighs 8.4 kg (18.5 pounds). When you add tube rings, dovetail bar, diagonal, eyepiece, and a finder you'll be looking at closer to 10 kg, which is substantial for a refractor this size. As such the scope needs a decent mid-weight mount. During my tests I used three German equatorials — the SharpStar Mark III (reviewed in last January's issue, page 64, and pictured with the Stellarvue scope), an Astro-Physics Mach 1, and the iOptron CEM 120 pictured with this review. All three worked very well,



and while the iOptron would seem like a bit of overkill I usually had the SVX127D mounted alongside my heavy, homemade 8-inch f/8 refractor (built around a triplet objective made by Roger Ceragioli). Comparing the views through both instruments was helpful for assessing the astronomical seeing conditions, but not especially meaningful beyond that given the significant difference in aperture.

Although I did use the Stellarvue for some casual deep-sky observing, most of my testing focused on solar system objects and binary stars — targets for which this type of instrument excels. I could go on at length about individual observations, but as every experienced observer knows, the seeing influenced the views as much as the scope's optical

▼ Left: The standard dual-speed Stellarvue 3-inch rack-and-pinion focuser includes two dovetail shoes for mounting finders. The author particularly liked that the whole focuser body could be easily rotated to keep the focus knobs horizontal. Right: The focuser drawtube extends a maximum of 115 millimeters, and the rack-and-pinion drive does not slip even when carrying heavy loads.



qualities. Nevertheless, during those times of good seeing, the SVX127D gave views that were particularly noteworthy for their sharpness and high image contrast. There were several occasions when I was especially impressed with how crisp and black shadow transits appeared on Jupiter, and how clearly defined details were within Saturn's rings.

Since my plan had been to test the scope as a visual instrument, we did not ask to borrow Stellarvue's optional field flattener or reducer/flattener, both of which produce imaging circles about 43 mm in diameter and are large enough for a full-frame DSLR camera. That, however, did not stop me from trying a few exposures of the Andromeda Galaxy with my full-frame Nikon D850 camera. With stars carefully focused at the center of the camera's frame, stars at the edge of the field showed typical



▲ The scope's metal lens cap threads into the sliding dew shield and thus can be attached when the shield is extended.

distortions due to the expected field curvature for an f/8 doublet objective. But setting the point of best focus about halfway between the frame's center and long edge (a well-known astrophotography technique) produced decent star images across much of the frame.

I believe many imagers working with cameras having modest-size detectors will be happy with the scope's performance without a field flattener.

When the SVX127D was mounted in my backyard observatory, I found it such a pleasure to use that I was always looking forward to opening the roof for spur-of-the-moment views of the Sun, Moon, and planets. The ready-to-use aspect of a refractor coupled with the superb optical and mechanical performance of the Stellarvue scope made it a real joy. I can highly recommend the scope for anyone in the market for a first-class 5-inch refractor.

■ Although DENNIS DI CICCO lives under the ever-increasing light pollution of Boston's western suburbs, it was not a handicap when observing the objects for which the Stellarvue scope excels.



▲ While the author did not test the optional field flattener made for the SVX127D, he still captured decent star images across much of the field of a full-frame DSLR by setting the critical focus point midway between the center and edge of the frame. This view of the Andromeda Galaxy is a stack of five 90-second exposures made with a Nikon D850 camera set at ISO 800.



◀ NIGHTVISION FILM

The Apache-Sitgreaves Research Center now offers red film sheets for your computer and other electronic-device screens. Sirius Red Film Computer Screen Light Shield (starting at \$24.95) is a transparent plastic sheet measuring 12 by 16 inches (30 by 40 centimeters). The film is affixed to your device screen with included rubber bands to dim the view and better preserve your night vision. Sirius Red Film is more transparent than Rubylith and provides a comfortable brightness level while imaging at the telescope. The film is a variation of “non-zero” blue transmission preferred by astrophotographers and outreach providers. Custom sizes are available at additional cost.

AS Research

apache-sitgreaves.org



◀ TABLETOP-COMPATIBLE

Celestron adds even more grab-and-go convenience for its NexStar telescope owners. The Tabletop Tripod (\$99.95) is a small base half the size and weight of the standard NexStar tripod, standing just 18 cm at its lowest setting while tipping the scale at just 3 kg (6.8 lbs). It opens to a 43-cm-by-41-cm footprint to ensure the same stability as the full-size model. The tripod's legs fold inward and stow neatly under the mount plate for easy storage and transport. Each foot has adjustable knobs, and there's a bubble leveler on the mount plate to ensure your setup is level before attaching your NexStar telescope. The Tabletop Tripod is compatible with the NexStar 4SE, 5SE, 6SE, and 8SE as well as the NexStar Evolution 6, 8, 8HD, Limited Edition 8HD, and 9.25 telescopes.

Celestron

2835 Columbia St., Torrance, CA 90503

310-328-9560; celestron.com



◀ MEGA MOUNT

PlaneWave Instruments announces its latest entry to its series of observatory-class robotic mounts. The T-600 Direct-Drive Gimbal (\$65,000) is a heavy-duty, direct-drive mount for serious imagers and researchers alike. The T-600 uses powerful direct-drive motors on each axis that can slew at speeds of up to 150° per second, allowing tracking of virtually any object in the sky. Additionally, high-resolution encoders on each axis ensure precise pointing and tracking with zero backlash and no periodic error. The T-600 is controlled by the ASCOM-compliant PWI4 software and can be mounted in Alt-Az, equatorial, and even Alt/Alt orientation while carrying instrument payloads on each side of its altitude axis. The mount comes standard with 2-layer, non-contact sealing at each motion surface and incorporates through-the-mount cabling. The T-600 weighs 274 kg and can bear loads of up to 272 kg.

PlaneWave Instruments

1375 North Main St., Bldg. #1, Adrian, MI 49221

310-639-1662; planewave.com

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Altair Astro's Herschel Wedge

Here's a white-light solar filter that works just as well with a camera as it does with an eyepiece.



Altair Imaging Ready 2-inch Solar Herschel Wedge V2

U.S. Price: \$359
altairastro.com

What We Like

High-contrast views of sunspots

Integrated variable polarizing filter

What We Don't Like

Camera rotates when adjusting polarizing filter

IT'S A GOOD TIME to be an observer of the Sun. Not only is the solar cycle ramping up, but North American observers will be treated to two solar eclipses visible across the continent during the next 13 months. It's also a good time to take stock of your Sun-observing gear and to think about any upgrades you have in mind before inventories possibly run low. This is why the Altair Imaging Ready 2-inch Solar Herschel Wedge V2 caught my eye.

I've been using front-mounted, white-light solar filters for more than two decades, and while assembling my observing gear recently, I became curious to see how the views they produce compare to a device inserted farther down the light path behind the telescope's objective lens.

How It Works

A Herschel wedge is a specially made white-light prism for use with refracting telescopes. (They are not recommended for use with reflectors because of the potential for concentrated, unfiltered sunlight damaging internal components.) First proposed by John Herschel in the 1830s, the design functions like a specialized star diagonal. Instead of a simple mirror or 90° prism, a Herschel wedge incorporates a trapezoidal prism that diverts a small percentage of the Sun's light to the eyepiece while passing the rest through the prism where it won't pose a threat to your vision. There are two caveats to the design that make it more complex than a full-aperture

► Altair Imaging Ready 2-inch Solar Herschel Wedge V2 is a white-light solar filter that works like a drop-in replacement for your star diagonal.

► The Altair Solar Wedge 2 comes in a custom, hard-shell carrying case with foam inserts. It ships with a 2-to-1½-inch eyepiece adapter and a 1¼-inch neutral density filter.

filter. The first issue is that the light directed towards the eyepiece is still too powerful to be safe for viewing, so it must be additionally attenuated. The other issue has to do with the excess light and heat diverted through the rear of the prism — this needs to be safely dispersed so that it doesn't burn anything (or anyone) who contacts the exiting beam. The Altair Imaging Ready 2-inch Solar Herschel Wedge V2 does both, and does them very well.

The Altair Solar Wedge 2 is billed as "imaging ready" for several reasons. The first is its 2-inch-format, 46-mm clear aperture that provides a wide, unvignetted field that will illuminate a full-frame detector. Additionally, a 2-inch, circular polarizing filter is mounted at the base of the eyepiece turret, permitting you to quickly adjust the brightness of the view by turning the turret. This lets you quickly switch between levels comfortable for visual observing and brighter levels for imaging, when extremely short exposures are desirable. This setting can be locked with a thumbscrew, though I found it firm enough that I didn't need to lock it. The eyepiece turret, and the included 2-to-1¼-inch



eyepiece adapter, use brass compression rings to secure eyepieces or cameras without marring their barrels. Altair's Solar Wedge 2 requires 115 mm of back focus, which is only slightly more than a regular 2-inch star diagonal.

The rear of the wedge housing receives all the out-of-focus sunlight and diffuses it across a thick, polycrystalline ceramic disk that does double duty as a solar finder. The Sun appears as a bright spot on the white ceramic disk — centering the image here ensures it will also be well-centered in the eyepiece. Additional ventilation openings are located both above and below the disk.

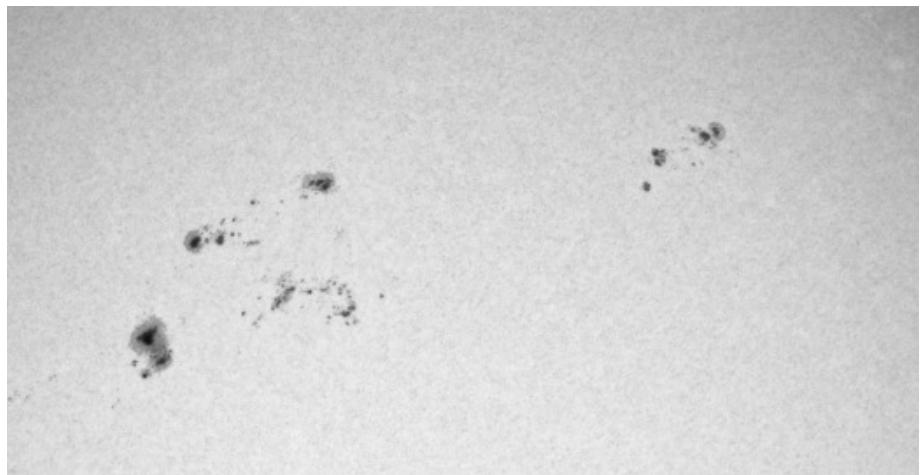
Under the Sun

The Altair Solar Wedge 2 quickly became my favorite white-light solar filter. Visually, the image is as good as the best views I've attained with Baader Solar Safety Film filters mounted in front of the objective. When I did side-by-side comparisons, I'd even say that at times the views through the wedge were better. Furthermore, I could easily swap the wedge between several of the other refractors I own — something you can't usually do with a single, front-aperture filter.

I also tested the Altair wedge against a full-aperture, glass solar filter using the same 92-mm refractor and the same eyepiece. The glass filter really couldn't compete with the wedge — the view was overall softer through the glass filter compared to the crisp, sharp view in the Altair wedge. Contrast was notably superior through the wedge as well.

When using the wedge on my 92-mm refractor, neither the ceramic diffusing disk nor the wedge body felt warmer than the surrounding air even after a couple of hours of use. I put the company's advertising claims to the test by using the filter with my 6-inch refractor when the Sun was high. After an hour the wedge was quite warm to the touch but not too hot to handle — more like a freshly baked loaf of bread.

Imaging with the wedge was extremely easy. I simply added a Player One Apollo-M solar camera into the focuser, as well as a tele extender to



▲ Sunspots, surface granulation, and some plage regions are visible in this view recorded on the morning of October 7, 2022. The Altair wedge was paired with a 92-mm Astro-Physics Stowaway refractor and the Player One Neptune-C II planetary video camera.

help increase the image scale on the camera's detector. When observing visually with the wedge, I preferred setting the polarizer near its strongest setting and using the opposite setting with the camera to achieve extremely short exposures. Imagers should note that rotating the eyepiece turret to adjust the polarizing filter also rotates the camera. Altair includes an additional 1 1/4-inch neutral density filter, but I never found the view bright enough to require extra attenuation, even when using the wedge with my 6-inch refractor.

Images captured with this setup

rendered the solar surface as a sea of granularity, with small, bright plage nearer to the limb and lots of crisply detailed sunspots.

After several months of use, I find myself reaching for the Altair Solar Wedge 2 instead of my front-aperture white-light filters. The integrated variable polarizer makes fine-tuning the brightness of the view quick and easy. Highly recommended!

■ Contributing Editor RICHARD WRIGHT loves solar observing except for the sweat it generates.



▲ Using the Altair Solar Wedge 2 for several hours with a 6-inch refractor made the gadget warm but not hot enough to be harmful.

◀ The back of the wedge contains a polycrystalline ceramic disk to diffuse the heat from the out-of-focus sunlight diverted from the optical path. The disk also functions as a finder — centering the Sun on the disk does the same in the eyepiece.

Easy, Large, Unobstructed Binoculars

Here's a simple project for big Dobs.

ANYBODY FAMILIAR with my column knows that I'm a bit of a binocular nut. The view through two eyes impresses me much more than the view with one eye closed.

Minnesota ATM Carl Anderson is a bit of an unobstructed reflector nut. An optical path without a secondary mirror or spider vanes provides a crisper, more contrasty view than one with diffraction effects muddying the image. For example, you can convert a 25-inch f/4 Newtonian into an unobstructed and diffraction-limited 10-inch f/10 telescope simply by adding a 10-inch off-axis mask in front of the scope, being careful not to let the spider vanes or secondary mirror intrude into the light path. Sure, you lose a lot of light when you do that, but you've got the equivalent of a very, very expensive 10-inch apochromatic refractor.

Imagine doing that with both sides of your primary and using a binoviewer to give each eye its own unobstructed 10-inch scope!

I'm not normally a fan of binoviewers. The designs I've seen all use beam splitters to divide the incoming light cone in two and send a half-strength copy off to either eye. The result is exactly the same view in both eyes, which doesn't provide the dynamic integration that happens in your brain when each eye is seeing a slightly different image. Plus, the contrast always seems to suffer, and often the extended light path requires a Barlow to bring

► With the Orion binoviewer, the light path is split into two discrete beams, each showing a single side of the telescope.

it to focus. That means you can't get a wide-angle view, which is where binocular scopes really shine.

Fortunately, Carl discovered the Orion Premium Linear BinoViewer (reviewed in our May 2020 issue, p. 66). Rather than divide the same light beam into two, this model splits it in half, left-right. It also uses a relay lens to extend the light path, so it doesn't require additional back-focus, which means it can provide a generous, wide-angle view.

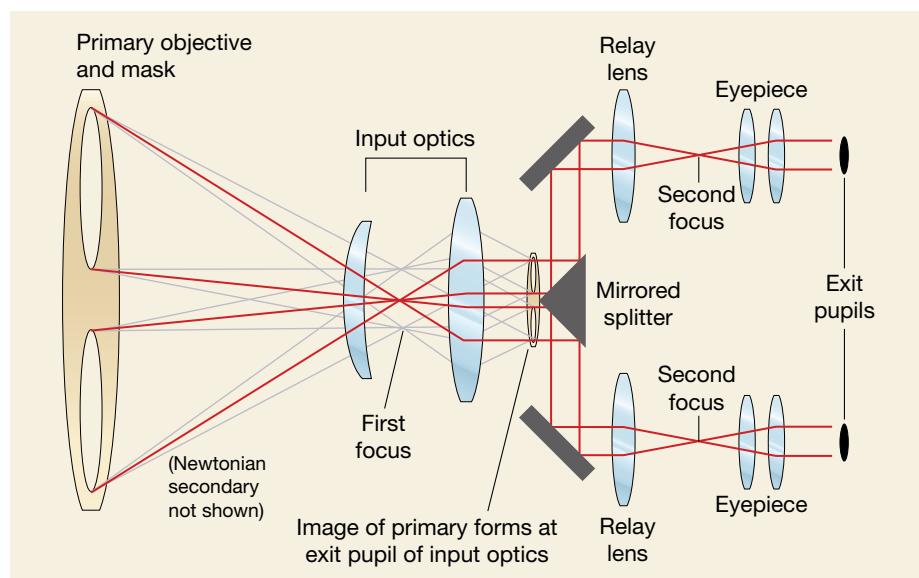
Without an aperture mask, the Orion binoviewer sends light from one side of the mirror to one eye and light from the other side of the mirror to the other eye. That results in odd, half-moon exit pupils, startling to some when they lean in for their first look. Plus diffraction effects from the secondary and spider vanes are still there.

Here's where Carl's idea comes into

▲ Carl Anderson's 25-inch Obsession telescope moonlighting as an unobstructed and diffraction-limited 10-inch binocular telescope. All that's required is the addition of his aperture mask and an Orion Premium Linear BinoViewer.

play. He puts a circular mask on the front of the scope that leaves two side-by-side, unobstructed apertures. With a 25-inch scope, those can be up to 10 inches across. With a 16-inch scope, you can do at least 6, maybe 6½ inches, depending upon your secondary-mirror diameter. Yes, you're throwing away a lot of light, but you're gaining a ridiculously inexpensive pair of very large binoculars. Not only that, but the aperture masks make the exit pupils round again.

You have to be careful to orient the binoviewer so it sees the full, unobstructed openings. An easy way to align it is to remove the binoviewer and look directly into the focuser. You'll see the





▲ The Orion Premium Linear BinoViewer uses a different technology than most, making this simple telescope modification possible.

two incoming light beams coming from the diagonal mirror. Then insert the binoviewer to match the orientation of the light beams.

Carl verified that the binoviewer is actually providing discrete images to each eye by covering first one, then the other aperture. Sure enough, first one eyepiece went dark, then the other.

How well does it work? Carl reports a noted increase in clarity when looking at objects with fine detail like planets or the Moon. This is undoubtedly due to the longer focal ratio of the individual optical paths (which provides more forgiving focus), to the mental processing that goes on when two eyes are involved, especially when those two eyes are looking through two different columns of air, and to the lack of diffraction-producing obstructions. The combined effect is crisper and much more pleasing than the full-aperture telescope with a single eyepiece.

Note that this won't work with traditional prism-style binoviewers. Those would actually increase diffraction effects due to combining light from the two mask apertures.

If you've got a big Newt with aperture to spare, give it a try. But hang onto your socks when you lean in for that first look.

For more information, contact Carl at stressedglass@yahoo.com.

■ Contributing Editor JERRY OLTON sometimes wishes he had four eyes.

The 2023 *Sky & Telescope* Observing Calendar is a comprehensive guide to the night sky. It features a central calendar page with a grid of dates and celestial events, surrounded by monthly covers for April, May, July, October, and December. Each cover is a vibrant, full-color photograph of a celestial object or scene. The April cover shows a solar eclipse, the May cover shows a nebula, the July cover shows a planetary alignment, the October cover shows a star cluster, and the December cover shows a planetary conjunction. The calendar also includes a "Special Events" section at the bottom.

The 2023 *Sky & Telescope* Observing Calendar combines gorgeous astrophotography and special monthly sky scenes that illustrate the positions of the Moon and bright planets. It also highlights important sky events each month, including eclipses, meteor showers, and conjunctions. **Makes a great gift!**

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What Is Opposition?

IF YOU READ ABOUT Ceres on page 48, you may be wondering what it means when an object reaches *opposition*. The term generally means that a planet (or dwarf planet, in the case of Ceres) is approximately opposite of the Sun's position in our sky.

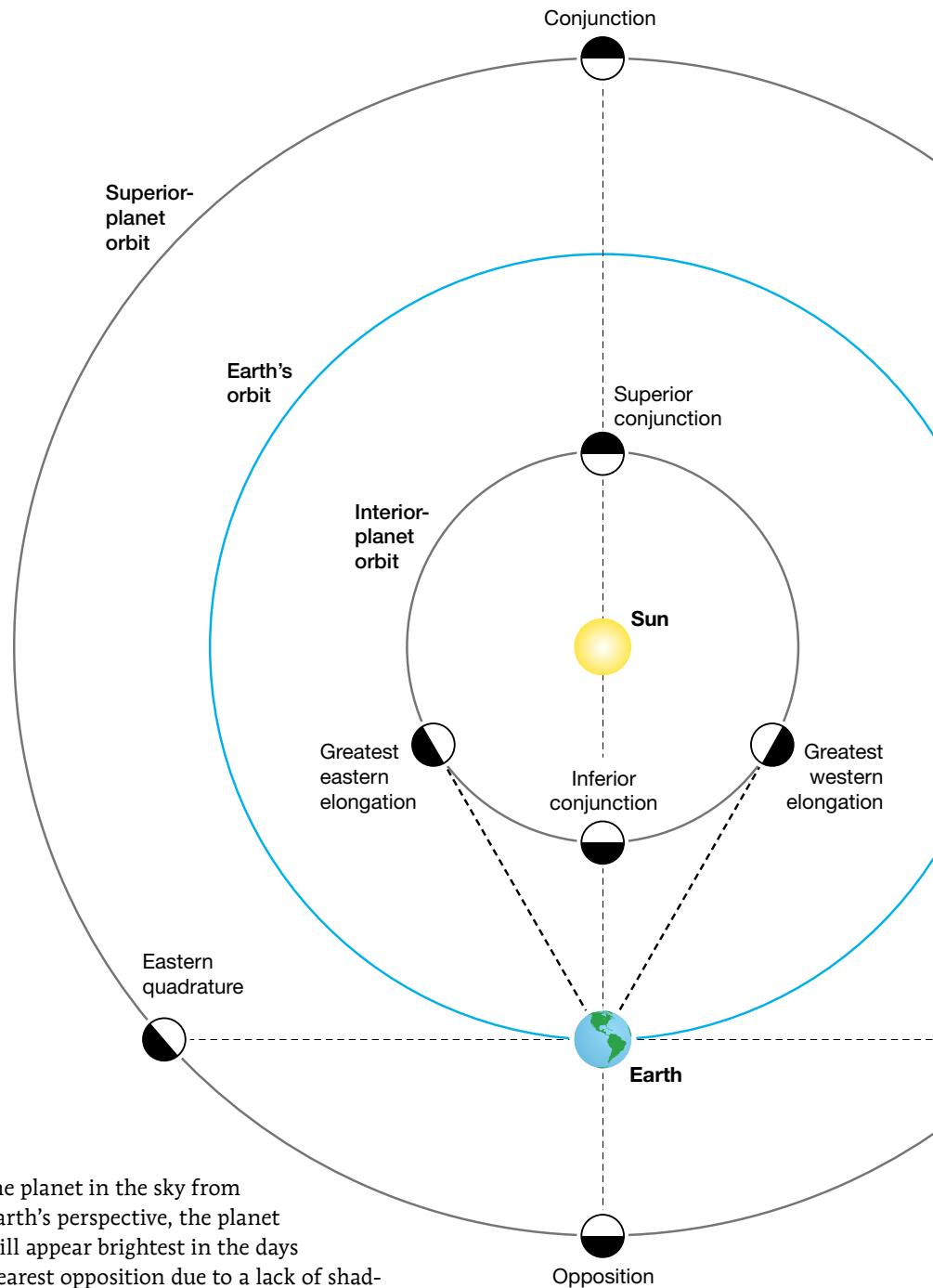
Simply put, all objects in our solar system, including planets, asteroids, and comets, orbit the Sun. Once each orbit, Earth is positioned between the Sun and any body that orbits farther out. This is the point when that body reaches opposition. It's also the best time to view these targets, because that's when the outer planets are closest to Earth in their orbits and appear at their largest due to their relative proximity.

There are a few ways to determine the exact time of opposition, but the commonly accepted way is based on planetary longitude, where the planet appears precisely 180° (or opposite) from the Sun.

Outer Superiority

There are two types of planetary orbits to consider. Only bodies orbiting farther from the Sun than Earth does can appear opposite of our star. The list includes Mars, Jupiter, Saturn, Uranus, and Neptune. These are called the *superior planets*, a term that originated long ago, before astronomers understood that the planets orbit the Sun rather than Earth. The dwarf planets Ceres and Pluto also follow superior orbits, as do comets and most asteroids.

When a planet reaches opposition, it's visible throughout the entire night. In addition to a brightness boost because the planet is closest it comes to Earth in its orbit, there's an additional optical phenomenon that occurs at opposition. Because the Sun lies directly opposite



the planet in the sky from Earth's perspective, the planet will appear brightest in the days nearest opposition due to a lack of shadows as seen from our perspective, known as the *opposition effect*. All the outer bodies display the opposition effect, regardless of whether they're a rocky body like Mars or gas giants like Jupiter and Saturn.

Because the superior planets orbit farther from the Sun than our home world does, they always present their sunlit side towards us. But that doesn't mean they always look

▲ **OVERHEAD VIEW** The diagram above shows how objects in the solar system orbit around the Sun and how an observer's perspective from Earth determines the best times of year to observe the *superior* (outer) and *inferior* (inner) planets.

like complete disks. The outer bodies exhibit a *gibbous* phase (appearing convex) when they reach the points in their orbits when they are 90°

from the Sun, known as *quadrature*. This occurs at two points, first when Earth is catching up with the planet (the western quadrature) as it rises at midnight. Later, months after opposition, the planet is highest at sunset when it reaches eastern quadrature. All

the outer planets exhibit a phase at quadrature, though Mars appears most dramatically gibbous at 86% due to its comparative proximity to Earth. With the other outer planets, the phase is subtle even with high magnification in telescopes.

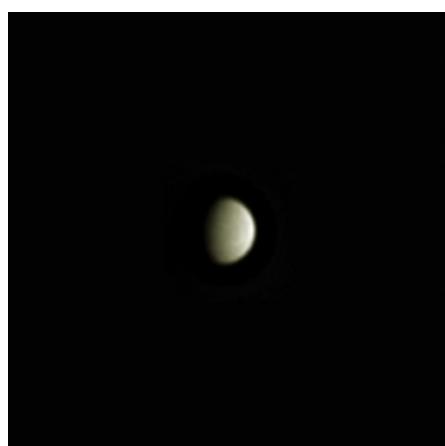
When an outer planet passes behind the Sun as seen from Earth's perspective, this is called *solar conjunction*.

Interior, not Inferior

Leaving aside opposition and the orbital geometry of the outer bodies, you might wonder about Mercury and Venus.

The two inner planets operate in the same way but exhibit a wide range of phases due to their nearer proximity to the Sun. The two were previously referred to as *inferior planets*, another relic of geo-

Western quadrature



▲ **OUTER APPARITION** The superior planets such as Mars appear biggest, brightest, and fully illuminated when they reach opposition (left), the point opposite in the sky from the Sun. Superior planets also display a gibbous phase as they approach and recede from opposition. The image at right shows Mars around the time of its western quadrature several years ago.

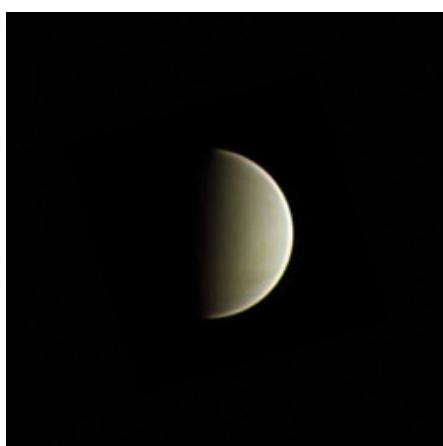
centric cosmology. Of course, we now understand that the two planets simply orbit closer to the Sun than Earth does and instead are today referred to as the *inferior planets* – there's nothing inferior about either world!

Since Mercury and Venus orbit closer to the Sun than Earth does, they can't reach opposition. Instead, they have two similarly notable points in their orbits. The first is known as *greatest elongation*, when the planet appears at its maximum angular separation from the Sun as seen from here on Earth. That's when they're easiest to locate and view (especially Mercury). Venus can reach a maximum distance of 47° from the Sun, while Mercury can appear as much as 28° from the solar disk. Much like the outer planets' quadrature, the in-

terior planets achieve western elongation as they catch up with us in our orbit, and an eastern elongation occurs when each passes us by.

Since the interior planets don't reach opposition, they can display the same set of phases as the Moon. They pass between the Sun and Earth once per orbit, a point known as *inferior conjunction*. On rare occasions, both Venus and Mercury can pass directly in front of the Sun, in events called *transits*. The interior planets also pass behind the Sun, a position known as *superior conjunction*.

Once you grasp the basic geometry of planetary orbits, you can use this information to plan when to get the best views of the planets and understand why they're sometimes out of view. ■



▲ **INTERIOR PHASES** Venus (shown) and Mercury orbit closer to the Sun so never reach opposition. Instead, we see their illumination change from a tiny, gibbous phase (left) to a half-lit globe near greatest elongation (middle), and even to a thin crescent as the planet nears inferior conjunction (right).



RECLINING SOUL

Mark Killion

Along the eastern border of Cassiopeia lies IC 1848, the Soul Nebula, an active star-forming region of glowing hydrogen gas and dust that bears a striking resemblance to a sleeping baby.

DETAILS: *Takahashi FSQ-130ED astrograph and Canon EOS Ra camera. Total exposure: 5½ hours at ISO 1600.*





△ ATMOSPHERIC BANDING

Soumyadeep Mukherjee

This composite of the partially eclipsed Moon of November 8, 2022, is enhanced to highlight color differences along the edge of the umbra.

DETAILS: Nikon 5600 camera with Sigma 150-to-600-mm zoom lens.

Stack of multiple exposures recorded at f/6.3, ISO 800.



△ LUNAR ATTENDANTS

John Volk

The eclipsed Moon of November 8th is seen surrounded by the stars of Aries and Cetus in this long exposure.

DETAILS: Takahashi FS-152 refractor and Canon EOS R mirrorless camera. Total exposure: 3 seconds at f/8, ISO 800.



△ INTO THE DARK

Michael Shapiro

At maximum totality, last November's total lunar eclipse — the last until 2025 — took on deep red and orange hues as seen from Michigan.

DETAILS: Celestron NexStar Evolution 8 Schmidt-Cassegrain and ZWO ASI294MC Pro camera. Stack of multiple video frames.



COLOR SWATCH

Chirag Upreti

Last November's eclipsed Moon is cleverly aligned with multihued lights on a building in New York City, with the reddish hues completing a playful series of color swatches.

DETAILS: Modified Sony α7 III camera with Sony FE 200-to-600-mm zoom lens. Total exposure: 0.6 second at f/6.3, ISO 640.

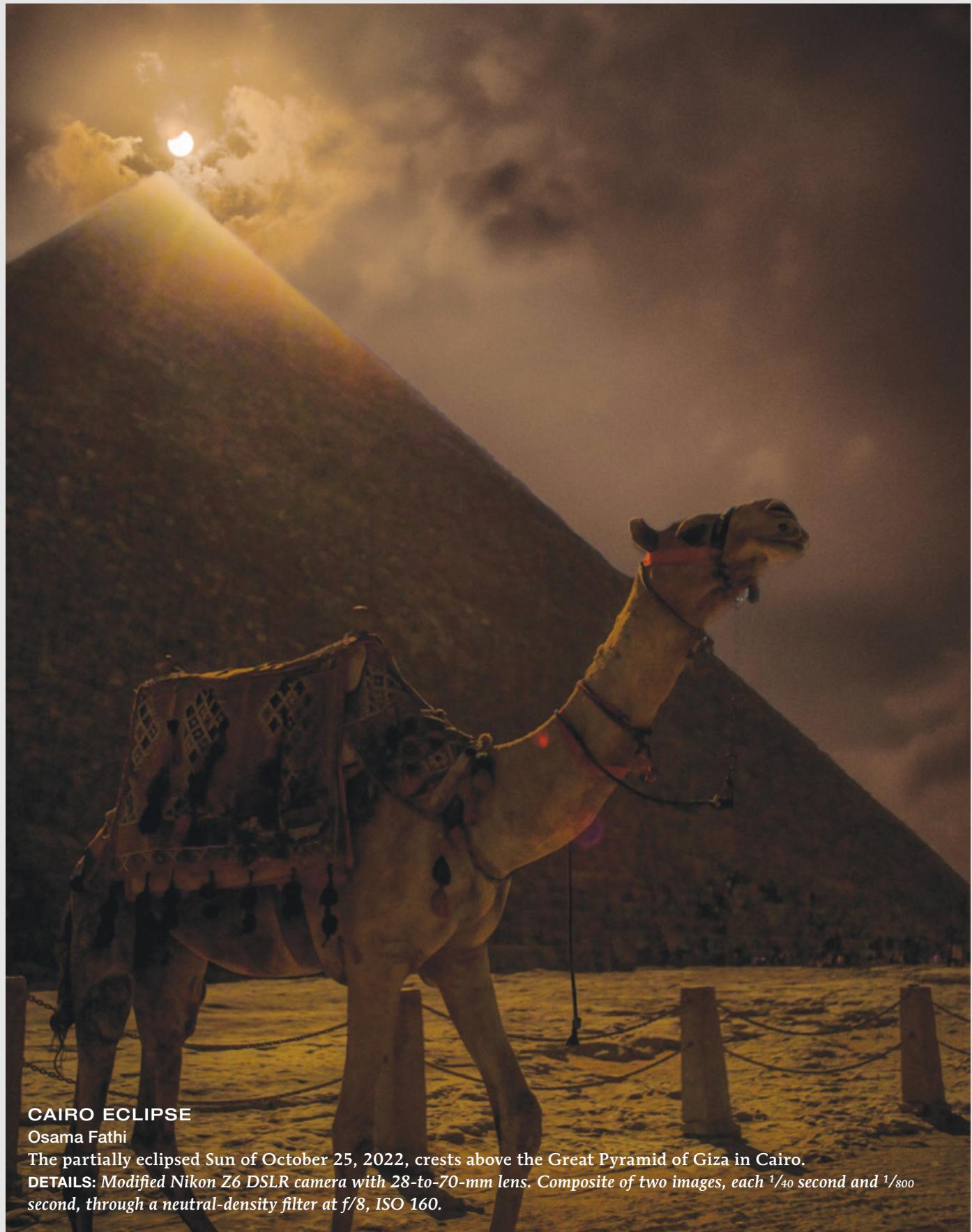


LUNAR ECLIPSE TIME-LAPSE

George Preoteasa

A total lunar eclipse descends behind the skyline of Manhattan on the morning of November 8th in this composite image. At the right, the Empire State Building towers over foreground skyscrapers. Mars also manages to cut through the light from the city at center left.

DETAILS: Sony α7 III camera with 50-mm lens. Composite of 40 images.



CAIRO ECLIPSE

Osama Fathi

The partially eclipsed Sun of October 25, 2022, crests above the Great Pyramid of Giza in Cairo.

DETAILS: Modified Nikon Z6 DSLR camera with 28-to-70-mm lens. Composite of two images, each $1/40$ second and $1/800$ second, through a neutral-density filter at $f/8$, ISO 160.



◁ FLYING DUMBBELL

Chris Schur

Many knots of gas and dust decorate the central regions of M27, the Dumbbell Nebula, in Vulpecula. This bright planetary nebula displays several faint shells of ionized hydrogen and oxygen expelled from its core.

DETAILS: Orion 10-inch astrograph and SBIG ST-10XME CCD camera. Total exposure: 14 hours through narrowband and RGB filters.

▽ HOT WINDS

Emil Andronic

Sharpless 2-119 is a large, bright complex of emission and dark nebulosity in Cygnus that almost appears to be caught in a windstorm. The bright star at the center, 68 Cygni, has ionized the surrounding gas and dust.

DETAILS: Teleskop-Service 65-mm quadruplet astrograph and QHY294M Pro camera. Total exposure: 23.42 hours through narrowband and RGB filters.



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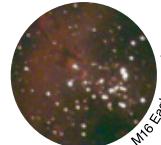
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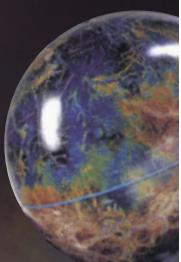
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Event Calendar

Here's the info you'll need to "save the date" for some of the top astronomical events in the coming months.



February 3-4

EUROPEAN ASTROFEST

London, England

europeanastrofest.com

February 13-19

WINTER STAR PARTY

Scout Key, FL

scas.org/winter-star-party/?y=2023

March 4

TRIAD STARFEST

Jamestown, NC

greensboroastronomyclub.org

April

GLOBAL ASTRONOMY MONTH

Everywhere!

<https://is.gd/astrowithnoborders>

April 15-16

NORTHEAST ASTRONOMY FORUM

Suffern, NY

neafexpo.com

April 19-22

MIDSOUTH STARGAZE

French Camp, MS

rainwaterobservatory.org/events

April 27-30

SOUTHERN STAR

Little Switzerland, NC

https://is.gd/southern_star

April 29

ASTRONOMY DAY

Everywhere!

<https://is.gd/AstronomyDay>

May 14-21

TEXAS STAR PARTY

Fort Davis, TX

texasstarparty.org

May 19-21

MICHIANA STAR PARTY

Vandalia, MI

michiana-astro.org/index.php/msp13

June 10-17

GRAND CANYON STAR PARTY

Grand Canyon, AZ

<https://is.gd/GrandCanyonStarParty>

June 14-17

BRYCE CANYON ASTRO FESTIVAL

Bryce Canyon National Park, UT

https://is.gd;brca_astrofest

June 14-18

ROCKY MOUNTAIN STAR STARE

Gardner, CO

rmss.org

June 14-18

YORK COUNTY STAR PARTY

Susquehannock State Park, PA

<http://yorkcountystarparty.org>

June 15-18

CHERRY SPRINGS STAR PARTY

Cherry Springs State Park, PA

<https://is.gd/CherrySprings>

June 15-18

WISCONSIN OBSERVERS WEEKEND

Hartman Creek State Park, WI

<https://is.gd/WIObserversWeekend>

• For a more complete listing, visit https://is.gd/star_parties.

Observer Extraordinaire

In September 2022, the author celebrated 41 years of nightly recording of aurorae — and he's not done yet.

IN 1981, when I began watching for the northern lights from my family home in Glen Ullin, North Dakota, I had no idea how long it would last. After a decade of these nightly vigils, *Sky & Telescope* ran an article I wrote about my efforts (*S&T*: Aug. 1991, p. 199). Following my 2,000th aurora observation in October 2003, Contributing Editor Charles A. Wood authored a follow-up piece (*S&T*: Aug. 2004, p. 123).

I persevered, the years marched by, and in late September 2022 I completed my 41st year of chronicling the northern lights from my home. As of the end of October 2022, I had recorded 2,494 aurora events since September 26, 1981.

While I've learned an enormous amount about aurorae in that time, the findings I outlined in my 1991 article still hold true. These include the fact that while most aurorae put on their

finest show between 11 p.m. and 1 a.m. local time, others look best just after dusk or before dawn. Also, while green or greenish white are the most common colors, followed by yellow and, more rarely, red, occasionally exotic colors such as orange, silver-gray, or violet make an appearance.

I continue to use the same scale I devised early on to record the extent of a display. In my system, a primary curtain reaching halfway to Polaris is a level 5 display, for example, while an auroral curtain or arc stretching all the way to the polestar is a level 10. Aurorae are dynamic and look chaotic, but I simplify them into four basic phases: the glow, the homogenous arc, the rayed arc, and "flaming/pulsating" patches. These phases can revert, skip, and repeat in a single night, depending on the strength of the display.

Moreover, I've found that the aurora extent and frequency in my sky, being one measure of the Sun's activity, appear to contribute to local weather out here. Aurorae often seem to trigger or at least can be followed by winds, which affect precipitation amounts and amplify temperature extremes. Those extremes can range from about minus 50°C (-58°F) to over 38°C (100°F).

I've also kept a watch for noctilucent clouds since 1993. That's the year I discovered what at the time was the southernmost sighting in North America of these rare clouds, which appear some 80 km (50 mi) high in the atmosphere. So far, I've recorded 120 twilight events of them of various extents and forms. I observed STEVE, which can form a narrow, sky-spanning luminous arch visible for most of an hour, long before the acronym was devised. I've also sketched and recorded activity on the Sun for many years, reaching my 10,000th day of doing this on June 4, 2017.

So what of the future? Aurora activity is much less frequent today than it was a few decades ago. I recorded just 7 aurora event nights in 2018, a mere 5 in each of 2019 and 2020, just 10 in 2021, and 16 in 2022 through October. Compare this to 127 event nights in 1990 and 148 nights in 1991 — the "year of the aurora" in North Dakota.

While the current solar cycle 25 will certainly have an auroral high point sometime before the cycle peaks in late 2025, I, like others, predict it will be nothing like the peaks of 1991 and 2001. So anyone adventurous enough to record the aurora from my state will very likely see much less of the phenomenon than I have.

JAY BRAUSCH continues his nightly watch in Glen Ullin, North Dakota.



AURORA RECORDER The author, pictured at right in one of the thousands of images he's taken of the northern lights from his hometown in western North Dakota, has won awards for his dedicated work, including the Merlin Medal from the British Astronomical Association in 1993.





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